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Economic Geology

and the

Bulletin of the Society of Economic Geologists

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A SUMMARY OF IDEAS ON THE ORIGIN OF NATIVE COPPER DEPOSITS[1]

HENRY R. CORNWALL

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ABSTRACT

Native copper occurs in a wide variety of environments that includes mafic lavas, hypabyssal diabasic intrusives, ultramafic intrusives, clastic sedimentary rocks, and the oxidized zone of sulfide deposits. Native copper is the predominant copper mineral in mafic lava flows, best exemplified in the Lake Superior region, and in some sedimentary rocks, but it is typically subordinate to sulfide copper in other types of deposits.

Possible natural origins of native copper include: precipitation from sulfide-bearing hydrothermal solutions in rocks containing ferric oxide; deposition from sulfur-deficient magmatic or hydrothermal solutions; deposition from meteoric or hydrothermal chloride solutions in the presence of calcite, prehnite, or zeolites; precipitation from hydrothermal solutions by ferrous salts; organic precipitation from meteoric waters; reduction of copper sulfides by meteoric waters in the zone of oxidation; reduction of primary copper sulfides by later hydrothermal solutions.

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INTRODUCTION

Copper, silver, and gold are distinguished among metals in the earth's crust by their widespread occurrence and local abundance as the native metal. The commonness of native copper in Nature is rather surprising in view of the ease with which it combines with other elements, particularly sulfur, to form sulfides, carbonates, silicates, and other compounds. Also remarkable is the diversity of environments in which native copper occurs. The geologic associations of native copper, as shown in Table 1, range from mafic extrusives and intrusives to clastic sedimentary rocks, and to contemporary zones of weathering and meteoric waters.

The bibliography on native copper is extensive, but most of the authors limit their discussions to individual deposits. Lindgren (70; 71, p. 418–421, 514–528), however, gives careful consideration to the general relations and probable mode of origin of the most important types of native copper deposits. The present author has attempted in this paper to review briefly and evaluate, in the light of his experience, the various facts and theories that have been recorded concerning the occurrence and origins of this mineral. This is not a comprehensive review, but rather an appraisal of the information available as indicated by the included bibliography.

TABLE 1

Geologic Associations of Native Copper

Type and prominent examples	Number of occurrence cited in literature examined
1. Basaltic lavas and interbedded sedimentary rocks	34
Lake Superior district, U.S.A.	
Southeastern U.S.A. (Catoctin)	
Connecticut (Triassic)	
Copper and White Rivers, Alaska	
Coppermine River, Northwest Territories, Canada	
Novaya Zemlya, U.S.S.R.	
2. Diabasic hypabyssal intrusives	6
New Jersey (Triassic)	
3. Ultramafic intrusives	4
Monte Catini, Italy	
4. Clastic sedimentary rocks	8
White Pine, Michigan	
Corocoro, Bolivia	
Calumet and Hecla, and similar conglomerates, Michigan	
5. Oxidized zone of sulfide deposits	numerous
Santa Rita district, New Mexico	
6. Modern swamps	3
Cooke, Montana	

The association of native copper with basaltic lavas is common and widespread, as indicated in Table 1 by the number of occurrences cited in the literature examined (see Bibliography). In many lava sequences, native copper occurs as low-grade disseminations or small isolated masses. In several districts the deposits approach commercial size and grade, and on the

Keweenaw Peninsula in the Lake Superior district six deposits in lavas have profitably yielded, together, over 5 billion pounds of copper in the past 100 years.

Native copper is a prominent constituent of deposits in clastic sedimentary rocks that are locally sufficiently rich and large to be important commercially, as for example in the White Pine deposit in the Nonesuch shale of Michigan, and at Corocoro, Bolivia. The Calumet and Hecla conglomerate, in the Lake Superior district, has yielded over 4 billion pounds of copper; this conglomerate lies between two lava flows and may have more in common with the deposits in lavas than with those in sediments. In the remaining types of occurrence, native copper does not form large ore bodies.

The wide variety of conditions under which native copper may form indicates that it is stable within an appreciable range of physical and chemical environments, including: 1) those that accompany the cooling of a lava flow; 2) low to medium temperature hydrothermal environments; 3) ground water in the lower part of the zone of oxidation; 4) reducing waters in the bottoms of lakes, swamps, and shallow seas.

TABLE 2

POSSIBLE NATURAL ORIGINS OF NATIVE COPPER

1. Deposition from sulfide-bearing hydrothermal solutions in the presence of ferric oxide in the host rock (19, p. 711; 22, p. 129–142; 129).
2. Deposition from hydrothermal solutions deficient in sulfur (27, p. 197–198; 70, p. 689; 71, p. 418).
3. Deposition from chloride solutions in meteoric or hydrothermal waters in the presence of calcite, prehnite, or zeolites (42; 62, p. 847–873; 92; 93).
4. Deposition from hydrothermal sulfate solutions by the action of ferrous iron (115).
5. Organic precipitation from meteoric waters (76).
6. Reduction of copper sulfides and oxides by meteoric waters in the zone of oxidation of sulfide deposits (40, p. 176–177; 46, p. 159–167; 71, p. 843).
7. Reduction of primary copper sulfides by later hydrothermal solutions (59, 94).

A number of geologists have investigated or considered the mode of formation of native copper in these very diverse environments. The principal theories of origin that have been published are summarized in Table 2. All the postulated origins are based upon the geologic characteristics of specific individual natural occurrences, and the chemical explanations for several have been substantiated experimentally. The widely varied origins are most clearly illustrated by small isolated occurrences of native copper. The largest deposits, namely those in the Lake Superior district of Michigan and those at Corocoro, Bolivia, are more complex, and the available geologic data are compatible with more than one theory of origin.

In the following paragraphs the different types of native copper occurrence under the headings listed in Table 1 will be discussed.

NATIVE COPPER IN BASALTIC LAVAS

Scattered throughout the world are more than 30 areas of basaltic lavas that contain native copper, some of which occurs in deposits of potential commercial importance. The individual occurrences are listed in Table 3. Cer-

tain characteristics common to most of the areas suggest a close genetic relationship between native copper and mafic lavas. In 15 of the areas listed in Table 3, for example, the authors report that certain flows contain moderate amounts of finely disseminated primary native copper, whereas the remaining flows contain little or no visible copper. This concentration of native copper in certain individual flows of a sequence serves to identify these flows in the same manner that other unique compositional or mineralogic features charac-

TABLE 3

NATIVE COPPER OCCURRENCES ASSOCIATED WITH BASALTIC LAVAS

Locality	Reference
Canadian Arctic	
Coppermine River	Douglas (35), O'Neill (91)
Bathhurst Inlet	Duncan (36), Norrie (89)
Labrador, Canada	
White River, Alaska	Knopf (58)
Copper River, Alaska	Schrader and Spencer (105), Moffitt (81, 82), Bateman and McLaughlin (7)
Cap d'Or, Nova Scotia	Dawson (33)
First Mountain, New Jersey	Lewis (66, 67), Weed (128)
Connecticut	Butler, and others (22)
Southeastern U.S.A. (Catoctin)	Watson (127), Stose (116), Weed (128)
Lake Superior district, Michigan	Lane (62), Butler, and others (22)
Northeastern Oregon	
Triassic lavas	Lindgren (68)
Miocene lavas	Waters, A. C. (personal communication)
Mt. Meadows, Lassen County, Calif.	Kinkel, A. R., Jr. (personal communication)
Northern California (metamorphosed basalts)	Turner (12)
Comobabi Mountains, Arizona	Butler, and others (22)
Baggs Creek, Montana	Billingsley and Grimes (14)
Saõ Paulo, Brazil	Hussak (56)
Parana, Brazil	Leonardos (65)
Tolima, Colombia	Reymond (99)
Faroe Islands	Cornu (26)
Dalane, Norway	Neumann (86)
Serbia, Yugoslavia	Lazarevic (64)
Oberstein, Germany	Hintze (53)
Wielki, Mydsk, Volhynia, Poland	Malkowski (77)
Glarus, Switzerland	Amstutz (4)
Stirling, Scotland	Hintze (53)
Novaya Zemlya, U.S.S.R.	Voit (125), Alferov (3)
Urals, U.S.S.R.	Zavaritsky (134)
Siberian lava platform, U.S.S.R.	Moor (83)
Dzhida, Trans-Baikal, U.S.S.R.	Beck (8, 9)
Komandorski Islands, U.S.S.R.	Morozewicz (85)
Szechuan and Yunnan, China	Chu (25)
Queensland, Australia	Beck (9)
New Guinea	Beck (8)

terize other individual flows. Thus the copper content and mode of occurrence appear to depend on the source and petrologic history of the flow just as do other inherent peculiarities of the rock. Another common characteristic is that copper, both as native copper and as copper sulfides, is most abundant in the pegmatitic and vesicular parts of the flows (17, p. 512, 517, 525; 22, p. 46; 27, p. 177, 183, 197). Also, the mineralogy of the copper occurrences is similar everywhere. The secondary minerals associated with native copper

are, in approximate order of decreasing abundance, calcite, quartz, epidote, chlorite, prehnite, chalcedony, zeolites, and datolite.

Where sulfides are present in basaltic lavas, chalcocite, the sulfur-poor sulfide, is much more common than chalcopyrite or bornite, which suggests a deficiency of sulfur in the lava environment. Sulfides are reported to be relatively abundant in 10 localities (northeastern Oregon; New Jersey; Connecticut; Virginia; White River, Alaska; Szechuan and Yunnan, China; Tolima, Colombia; Biloela, Queensland; Oberstein, Germany).

The copper in mafic lavas may be classified into two general categories: 1) primary disseminations of copper, mostly in the native state, that crystallized as the lava solidified; and 2) epigenetic concentrations of native copper that are in or adjacent to permeable zones in the lava sequence.

The two types of copper occurrence are well illustrated in the Lake Superior copper district, although it may not always be possible to determine in which category a particular grain of copper belongs. The massive rock in the interiors of the flows contains from 10 to over 400 ppm (parts per million) of copper, dominantly as interstitial grains finely disseminated through the rocks (17, 18, 27, 28, 29). Certain flows are characteristically rich in disseminated copper and others are lean; moderate concentrations of copper are found in pegmatitic segregations that occur in some of the flows.

In the many polished sections examined microscopically, the visible copper mineral is most commonly the native metal (28, p. 57–58). Comparison of rock analyses with spectrographic analyses of trace elements in mineral separations of the lavas, however, indicates that a third or more of the primary copper is concentrated in individual minerals and may have entered the crystal lattice of certain silicates and oxides (30). This copper is abundant in certain minerals and scarce in others. In seven analyzed rock samples, ranging in composition from basalt to pegmatite and granophyre, copper is most abundant in magnetite, where it ranges from 200 to 880 ppm. The remaining minerals contain copper in the following amounts: ilmenite, 90 to 300 ppm; augite, 51 to 320 ppm; chlorite, 50 to 280 ppm; plagioclase, 20 to 73 ppm.

The distribution of the disseminated copper in the flows and its concentration with other chemically related elements (such as Fe, Ti, P, Mn, V) in the pegmatitic facies and in certain minerals, indicates that this trace copper crystallized directly from the basaltic magma or its residual solutions, and a logical explanation of its native state is that the depositing medium was deficient in sulfur. The writer (27, p. 197–198) has followed Lindgren (70, p. 689; 71, p. 418, 420–421) in suggesting that sulfur was lost to the lava as a gas during the extrusion and crystallization process. This explanation of the native state seems to have more universal application than the theory of reduction by ferric oxide in the host rock (see 1, Table 2), inasmuch as native copper occurs in many lavas that do not have red, oxidized flow tops or interiors. This sulfur deficiency in lavas is in contrast to the situation in mafic intrusive bodies where disseminated copper typically occurs as a sulfide, either chalcopyrite or bornite. Though many exceptions can be cited, native copper is characteristically associated with lavas, and copper

sulfides with intrusive bodies; these associations are sufficiently universal to suggest strongly that where native copper is concentrated in or adjacent to lavas, the ultimate source of this copper may be the lava itself, rather than some remote intrusive rock.

Native copper also occurs as epigenetic concentrations in or adjacent to permeable zones in lava sequences such as those in the Lake Superior copper district. The commercial deposits of this district are found principally in (1) the fragmental layer, once rubbly, but now filled with secondary minerals, at the tops of certain lava flows; (2) conglomerates lying between some of the lava flows; and (3) veins (fissure deposits) that cut the sequence of lava flows almost at right angles to the layering. The deposits have been described in detail by a number of geologists (19, 22, 62, 96, 97) and need not be elaborated here. That the deposits are epigenetic and their location controlled very largely by permeability of the host rocks seems well demonstrated (19, 22). The ultimate source of the copper, however, is less clear. The principal theories and arguments that have been presented can only be touched on in this brief review of the types and outstanding characteristics of native copper deposits. The writer and his colleagues are preparing a more complete discussion for their report on the Michigan copper district.

Pumpelly (96, 97), Wadsworth (126), and Lane (62, p. 847–873) have suggested that copper present in minute amounts as a primary constituent in lavas or associated clastic sedimentary rocks of the Lake Superior district was leached from these rocks by surface waters and precipitated in permeable zones (fissures, vesicular and brecciated flow tops, interbedded conglomerates and sandstones) during downward circulation of the waters. Lane (62) assumed that the water was primarily sea water, imbibed into the cooling lava pile.

Smyth (111), Butler and others (22, p. 118–145), and Broderick and others (19) have, on the other hand, postulated a hidden body of magma at depth as the source of copper-bearing emanations, which ascended along permeable zones in the tilted lava sequence and deposited copper where conditions were favorable. Butler and others (22, p. 118–145), and Broderick and others (19) postulate that the sulfide-bearing solutions reacted with wall rocks (flow tops and interbedded sedimentary rocks) rich in ferric iron with the result that the iron was reduced, the sulfur oxidized, and native copper precipitated. Wells (129, p. 40–41) tried unsuccessfully to reproduce this reaction experimentally. Native copper has been precipitated experimentally, however, by the reducing action of ferrous sulfate on a solution of copper sulfate at 200° C (115, p. 647) and also by cooling cuprous sulfate solutions (129, p. 39).

Lindgren (71, p. 525) pointed out the following difficulties presented by the theory of magmatic origin: (1) the enormous amount of magmatic water required; (2) the unsatisfactory explanation of the chemistry of the proposed process of copper deposition—copper could be formed experimentally only in the presence of solutions of improbable acidity; and (3) no fissure veins with similar mineralization and oxidation of sulfur are known from

other parts of the world. He cites the probability that strongly active hot waters ascending through thousands of feet of basaltic rock will dissolve appreciable quantities of trace copper, and elsewhere (71, p. 517) says that "the suggestion that the whole or a part of the copper in the deposits was extracted by waters from the rock itself almost forces itself upon the observer."

As suggested above, the typical native state of copper in lavas in general points strongly to the lavas themselves as the source for the native copper that was later concentrated in the copper deposits in the Lake Superior district. The geometry of several deposits in the Lake Superior district strongly supports the view that the copper-bearing solutions ascended to the point of deposition (19, p. 696–697; 22, p. 115–116). Presumably, such ascending waters would be heated, with or without the assistance of magmatic heat. If the interstices of the porous flow tops and the interbedded sediments were filled with ground water as the lava series accumulated, many cubic miles of water were carried to depths from which they could later be driven out by heating and compaction. (W. S. White, personal communication.) Connate water of this origin seems a reasonable alternative to magmatic water, and, unlike magmatic water, need not contain any significant amount of sulfur to be explained away. The high chloride content of the present mine waters in the Michigan district suggests the possibility that the ore-bearing solutions may have been chloride rather than sulfide waters (62, p. 774–846). Copper would be considerably more soluble in chloride solution than in sulfide; native copper has been precipitated from copper chloride solutions at 200–250° C in the presence of prehnite, calcite, or zeolites (42, 92, 93).

To sum up, the native copper deposits of the Keweenaw Peninsula, Michigan, were almost certainly formed in permeable channelways by hot ascending solutions, whose composition has not yet been demonstrated. The native state of copper strongly suggests its derivation from the lavas themselves; lavas all over the world are characterized by the native state of the traces of copper that they contain, a state that is presumably due to loss of sulfur during extrusion. It does not seem necessary to postulate a magmatic source for much or all of the solutions that deposited the copper; connate waters, driven upward by heating and crushing in the more deeply buried parts of the lava series, provide a more reasonable alternative. It would appear, in fact, unlikely that the permeable lava sequence with interbedded water-deposited sediments was downfolded and buried without the entrapment of considerable amounts of connate water. Other native copper concentrations that may well represent a similar reworking during slight to moderate metamorphism are well illustrated in the Nicolai greenstone of the Copper River district of Alaska (7, 79, 81, 82, 105) and in the lavas of the Catoctin of eastern United States (116, 127, 128).

NATIVE COPPER IN HYPABYSSAL MAFIC INTRUSIVES

Hypabyssal intrusions of diabase, gabbro, and related rocks locally contain small amounts of native copper generally associated with copper sulfides. Several occurrences are listed in Table 4. The native copper occurs as dis-

seminated grains and as fillings of seams and vesicles with calcite and prehnite. At Zwickau, Saxony, and in New Jersey at Arlington and New Brunswick the copper occurs in disseminations and veins in tuffs, sandstones, and shales near intrusions of diabase or basalt. The host rocks in these occurrences are commonly bleached around the copper.

Sulfides predominate in these intrusions, but the local occurrence of disseminated native copper indicates a slight deficiency of sulfur when the copper crystallized (probably during the deuteric stage). A shallow depth of intrusion probably permitted the volatile constituents, including sulfur, to

TABLE 4

NATIVE COPPER OCCURRENCES

Locality	Reference
Associated with hypabyssal mafic intrusives	
Algodones, Chile	Möricke (84)
Oslo, Norway	Vogt (124), Beyschlag and others (12, p. 934)
Zwickau, Saxony	Beck (9, p. 234)
Pari, Tuscany	Lotti (75, p. 354)
Zululand, South Africa	Beyschlag and others (12, p. 346)
New Jersey, U.S.A.	Lewis (66, 67)
Associated with ultramafic intrusives	
Tuscany, Emilia, Liguria, Italy	Stelzner (114), Cortese (32)
Shizunai mine, Hidaka, Hokkaido, Japan	Kobayashi (59)
Vetica, Colombia	Schreiter (106)
Saint-Véran, Hautes-Alpes, France	Routhier (103)
In clastic sedimentary rocks	
Nonesuch shale, White Pine, Michigan	White and Wright (131)
Calumet and Hecla conglomerate, Michigan	Butler and others (22)
Houghton conglomerate, Michigan	Cornwall and others (31)
Red beds, southwestern U.S.A.	Bastin (5), Finch (43)
Boleo, Lower California, Mexico	Touwaide (120), Locke (74)
Corocoro, Bolivia	Singewald (109, 110), Ahlfeld (1), Entwistle and Gouin (41)
Helgoland Island, Germany	Schreiter (107)
Biel, Spain	Romero (102)
In modern swamps	
Cooke, Montana	Lovering (76)
Jefferson City, Montana	Forrester (45)
La Plata, Colorado	Eckel (37, p. 55)

escape rather freely. In the New Jersey deposits, Lewis (66, 67) considered that magmatic solutions containing cuprous sulfate and ferrous sulfate deposited native copper on cooling.

NATIVE COPPER IN ULTRAMAFIC INTRUSIVES

The ultramafic intrusives at the locations listed in Table 4 contain small amounts of native copper. The most common occurrences are in Tuscany, Emilia, and Liguria, Italy, where a number of serpentinite intrusives with associated diabase and gabbro are found (32). There the largest copper de-

posits, of which Monte Catini is the best known, occur in the larger intrusions and consist predominantly of slickensided bodies of massive chalcopyrite and bornite sheathed in crusts of chalcocite and native copper. Native copper also is disseminated and in small masses near the sulfide bodies. The serpentinite has been locally reddened near the native copper (114). Primary chalcopyrite and bornite segregations probably were altered to chalcocite and native copper by hydrothermal solutions that also oxidized the serpentine. Pieruccini (94) believes that the formation of native copper was related to the oxidation of ferrous iron in a sulfate solution.

At the Shizunai mine, Japan, balls of native copper weighing as much as 200 kilograms (440 pounds) occur at the margin of a serpentinite body in the wall rock and in clays derived from weathering. Kobayashi (59) believes that the native copper was formed by secondary enrichment by ascending hydrothermal solutions. At Vetica, Colombia, veinlets of native copper with quartz and epidote occur in serpentinized pyroxenite. Schreiter (106) considers that the copper mineralization was related to serpentinization, and that the reduction of copper was effected by ferrous salts in hydrothermal solutions.

The similar characteristics of all the native copper occurrences in ultramafic intrusives indicate a common process of formation, namely, the reduction of older, possibly magmatic copper sulfides by hydrothermal solutions. The hydrothermal solutions probably acquired ferrous iron as they traversed and serpentinized the peridotite. The locally reddened rock around the copper masses at Monte Catini indicates a reaction between copper sulfide segregations and hydrothermal solutions containing ferrous iron that produced ferric oxide and native copper (94).

NATIVE COPPER IN CLASTIC SEDIMENTARY ROCKS

Copper deposits in sandstones and shales, commonly far removed from igneous rocks, are important in widely scattered parts of the world. The literature on these deposits is voluminous and has been summarized by Lindgren (71, p. 403–417), Bastin (5, p. 411–429), Yagovkin (132), and others. For the most part these deposits consist predominantly of copper sulfides. In some deposits native copper is a minor constituent, and in a few it is important. Only the deposits containing native copper are listed in Table 4 and will be discussed here.

One of the largest and commercially most important sedimentary copper deposits with native copper is the White Pine deposit, which lies west of the main Lake Superior native copper district, near Ontonogan, Michigan. Two to five thinly laminated to massive black shale beds, each ranging from 2 inches to 4 feet in thickness, in the lowermost 25 feet of the gently dipping Nonesuch shale, contain disseminations of chalcocite with minor amounts of native copper. As individual beds are followed toward the margins of the ore deposit, they first lose their native copper, then their chalcocite, and finally they become sparsely pyritic. The ore averages slightly over 1 percent copper. The abundance of copper and the ratio of native copper to chalcocite shows no apparent relationship to structure or permeability. White and Wright (131)

believe that this deposit is essentially syngenetic and that the copper was deposited at or soon after the time of deposition of the shale in which it occurs. Native copper in the chalcocite ore indicates either reducing conditions at the time of deposition, a deficiency of sulfur in the depositing waters, or later reduction by organic processes.

Sandstone beds below and within the shale sequence of White Pine contain copper, mostly as the native metal, whose distribution is very clearly related to structure. This copper is almost completely restricted to the southwest part of an anticline, just northeast of a major fault—the White Pine fault. It probably represents copper leached from shale on the downthrown side of the fault and deposited in permeable sandstone beds on the upthrown side, after hydrothermal transport up the fault zone, but a more deep-seated source for this copper is not ruled out (131, p. 706–708).

Other sedimentary copper deposits that contain native copper, among other copper minerals, are found at Biel, Spain (102), Helgoland, Germany (107), the Red Beds of southwestern United States (5, 43), Corocoro, Bolivia (1, 41, 109, 110), and Boleo, Lower California (74, 120). Native copper is only a minor mineral in the Red Beds and may be due to oxidation of original sufides (see: Native copper in oxidized ores). Native copper occurs only below the ground-water table at Boleo. The Biel and Helgoland deposits were probably deposited from circulating meteoric waters. Touwaide (120) believes that the clay beds at Boleo were mineralized by circulating connate waters that picked up copper from the interbedded tuffs.

The deposits of Corocoro, Bolivia, are of interest as the principal locality, outside of the Michigan district, where the native metal is a major ore mineral, though chalcocite has been the principal ore mineral for the last 35 years. The genesis of these deposits has been discussed at length by Singewald and Berry (110) and, more recently, by Entwistle and Gouin (41). The host rocks of the deposits are reddish to yellow or white terrestrial shales and sandstones that belong to two late Tertiary series, the so-called Ramos and Vetas. Entwistle and Gouin (41) describe an unconformity that establishes the Ramos as the older. Native copper is the principal ore mineral in the Ramos, and it was abundant in the oxidized zone, at least, of the Vetas. All the mine workings in the Ramos are probably within 200 meters of the pre-Vetas erosion surface, and Entwistle and Gouin suggest that the native copper in the Ramos may occur in a fossil zone of oxidation. Despite the fact that the only igneous intrusives in the area probably are older than the sediments, Singewald and Berry (110, p. 80) consider that the source of the mineralizing solutions is an underlying dioritic magma. Entwistle and Gouin (41) note the absence of alteration related to concentrations of chalcocite in reddish beds of the Vetas, the lack of relationship to faults or fractures, and the coincidence of ore shoots with channels in the sandstone beds. They suggest that the sulfide copper in the Vetas may be largely syngenetic, derived from erosion of older deposits in the subjacent Ramos.

The case for a syngenetic origin of even the deposits in the Vetas is far from conclusive. On the other hand, though the deposits may well be epigenetic, there is nothing positive in favor of a magmatic origin. It should

be noted that the chief gangue minerals of the deposit, other than the rock minerals, are gypsum, barite, and celestite, all typical constituents of gypsiferous beds such as might be expected in a red-bed sequence. The case for a magmatic source of the mineralizing solutions rests heavily on the extent of one's conviction that metals in such solutions are prima facie evidence of magmatic ancestry (110, p. 80).

The theory that magmatic sulfide solutions have been oxidized in hematitic host rocks to precipitate native copper has been advocated for both the Michigan copper deposits and for those at Corocoro, and the association of red host rocks and native copper at each place has been made an important element in arguments for this process at the other place (19, p. 711–712, 716–717; 22, p. 124, 130, 137, 142; 109). If, as Entwistle and Gouin (41) suggest, the native copper at Corocoro actually represents a mineral of modern and fossil surface oxidation zones, the mutual support of all arguments based on comparison of deposits in the two places may be invalid.

NATIVE COPPER IN OXIDIZED ORES

Native copper quite commonly occurs in small amounts in the weathering zone of sulfide deposits. In the sulfide ores of western North America, native copper is a common minor constituent of the oxidized zone, and it occurs directly above the zone of secondary chalcocite enrichment. Emmons (40, p. 176–178) and Lindgren (71, p. 842–844) discuss in general terms the occurrence of metallic copper in weathering zones, and Emmons (40, p. 199–251) describes the weathering effects in many hypogene deposits. One of the largest native copper deposits of this type was found in the Santa Rita district, New Mexico (72, p. 61–62, 306, 315–317), where native copper production in early days of the district amounted to millions of pounds.

Oxidation effects are most pronounced in the weathering zone of hypogene sulfide deposits because of the normal abundance of pyrite that dissolves in ground water to form the powerful reagents, sulfuric acid and iron sulfate. Native copper and its oxides and carbonates are also found in oxidized sedimentary copper ores, as, for example, at Naukat (2, p. 467–485; 60) and Dzezkazgan (133) in central Asia. Under appropriate conditions, any copper-iron sulfide deposit may develop native copper in its oxidation zone.

In regard to the manner in which native copper is formed in weathering zones, Lindgren (71, p. 843) and Emmons (40, p. 176) state that in the oxidation of chalcocite deposits, native copper is developed from cuprite by the action of ferrous sulfate as follows:

$$Cu_2O + 2\ FeSO_4 + H_2SO_4 = 2\ Cu + Fe_2(SO_4)_3 + H_2O$$

Also, native copper may be formed directly from chalcocite by the action of ferric sulfate:

$$Cu_2S + 3Fe_2\ (SO_4)_3 + 4H_2O = 2\ Cu + 6\ FeSO_4 + 4H_2SO_4.$$

Garrels (46) has recently discussed, in more or less quantitative terms, the chemical environment in the zone of oxidation and secondary enrichment of

sulfide deposits. He considers the reactions in the weathering zone to be dependent almost entirely on the *p*H and the oxidation-reduction potential of the environment. Copper, he believes, dissolves near the surface by oxidation of the sulfide to sulfate. Thence it migrates downward, precipitating en route in a variety of minerals, including native copper, as the environment changes from oxidizing at the surface to reducing at depth. The native copper stability field, dependent primarily on the oxidation-reduction potential, lies between the field of cuprite (Cu_2O) and that of chalcocite (Cu_2S). Accordingly, native copper should and, in fact, commonly does occur most abundantly near the base of the zone of oxidation and just above the zone of secondary chalcocite enrichment.

NATIVE COPPER IN MODERN SWAMPS

Three descriptions of modern deposition of native copper in sedimentary environments have been published. Forrester (45) describes a native copper deposit in a swamp near Jefferson City, Montana. The copper occurs in peat muck, bog iron, and associated alluvial gravels. The reducing environment of the peat and bog-iron swamp has precipitated native copper from percolating ground water. Copper is leached from oxidized outcrops of epigenetic veins upstream in rocks of the Boulder batholith. It is carried downstream as copper sulfate until it reaches the reducing environment of the swamp.

Galbraith (in Eckel and others, 37, p. 55) describes a similar deposit of native copper in a swamp near La Plata, Colo. Ground water that has percolated through rocks containing disseminated pyrite and chalcopyrite drains into the swamp, which is about half an acre in extent. Black muck in the swamp, as much as 5 feet thick, contains numerous irregular nodules and grains of native copper. The muck also contains nodules of ferrous sulfide (troilite ?). Galbraith believes that these minerals are precipitated by reactions between organic matter and copper and iron sulfates in the swamp waters.

A third modern deposit of native copper occurs near Cooke, Mont., and is described by Lovering (76). This deposit is in a bog near the headwaters of Clarks Fork in a glacial valley. The bog contains thin beds of black muck, full of organic remains, interlayered with sand and gravel. Native copper occurs only in the muck, where it ranges in size from minute specks to lumps more than an inch in diameter. The surrounding upland is well mineralized, and several bodies of pyritic copper ore crop out half a mile above the bog. Lovering believes that copper, derived from the oxidation of these outcrops, is carried downward as cupric sulfate by ground water until it reaches the bog where the copper is precipitated by organic material. He produced metallic copper experimentally from copper sulfate solutions by the action of bacteria from the bog. His experiments indicated that the native copper formed by the reaction of the waste products of bacterial metabolism with the solution.

CONCLUSIONS

This review of the literature on native copper deposits reveals not only that native copper occurs in a wide variety of environments, but also that the

processes of formation of the mineral must likewise be notably varied. The precipitation of native copper by the reaction of reducing materials in swamps with copper-bearing circulating surficial waters is demonstrated by present day observable processes. Not actually observable, but nevertheless quite certain, is the process of native copper formation in the oxidation zones of sulfide deposits by reactions taking place in circulating ground waters.

The origin of native copper in clastic sedimentary rocks, and in magmatic and hydrothermal environments is not completely manifest, and individual occurrences are plausibly explained by alternate hypotheses. In most cases, however, the available data support one hypothesis in preference to others, and in this paper the author has attempted to indicate the most probable origins after consideration of the evidence at hand.

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MINERALOGY AND PARAGENESIS OF THE URANIUM ORE, MI VIDA MINE, SAN JUAN COUNTY, UTAH[1]

EUGENE B. GROSS

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ABSTRACT

Ore at the Mi Vida mine, San Juan County, Utah, consists of uraninite, coffinite, montroseite, a new vanadium oxide mineral,[2] corvusite, and minor secondary minerals. The ore occurs within the matrix of the lower Chinle calcareous sandstones and conglomerates, which are colored dark gray to black by ore minerals and carbonaceous material. The primary ore minerals fill interstices in the sandstone and replace calcite and fossil wood. The replacement process was partly selective: much uraninite replaced carbonaceous debris, calcite, and detrital grains, and the vanadium minerals principally replaced calcite of the sandstone matrix. A few sulfides, pyrite, galena, and greenockite, appeared at the same time or slightly later than the primary ore. Replacement textures are common in the ore, but age relations are not clear in all cases.

[1] Publication approved by the Director, Raw Materials Division, U. S. Atomic Energy Commission.

[2] New vanadium oxide mineral, $V_2O_4 \cdot nH_2O$ (formula tentative), found by Stieff and Stern at La Sal No. 2 mine, and described briefly by Weeks and Thompson, U. S. Geol. Survey Bull. 1009-B, p. 54; throughout the report to be called V^{+4} oxide.

INTRODUCTION

THE Mi Vida uranium mine of the Utex Exploration Company is located 39 miles southeast of Moab, San Juan County, Utah. Access to the mining area is by way of U. S. Highway 160 for 32 miles southeastward from Moab, and thence 9 miles eastward on a mine haulage road to the deposit (Fig. 1).

Petrographic study of the Mi Vida mine has been in progress since March 1954, in the Grand Junction Mineralogy Laboratory of the Atomic Energy Commission. X-ray and spectrographic analyses of some ore minerals had been made as early as March 1953, by the U. S. Geological Survey.

Cooperation of C. A. Steen and of other members of the Utex Exploration Company and its former lessee, the Garwood and Gerlach Mining Company, is appreciated. Thanks are due J. I. McLelland for collecting many samples. Members of the Geochemistry and Petrology Branch, U. S. Geological Survey,

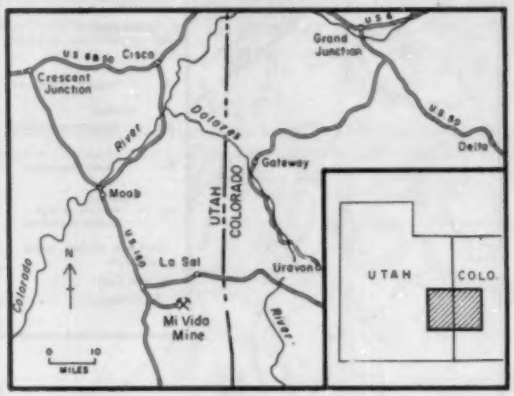

FIG. 1. Index map showing location of Mi Vida mine, San Juan County, Utah.

aided the work by chemical analyses of the uraninite samples, as well as X-ray determinations of montroseite and V^{+4} oxide.

STRATIGRAPHY

The Mi Vida mine ore zone is in the lower portion of the Chinle formation, which consists of siltstones, mudstones, fine- to medium-grained sandstones, conglomerates, and clastic limestones (calcarenites). The thickness of the Chinle formation ranges from 100 to 290 feet in the vicinity of the mine (1). It is overlain by the Triassic Wingate sandstone, and underlain by the Permian Cutler and Rico formations (Fig. 2).

STRUCTURE

The Mi Vida mine is on the southwest flank of the Lisbon Valley anticline, which plunges northwest and is faulted along its crest, the southwest

side being upthrown. The sedimentary strata dip 15° southwest on the west side of Big Indian Wash and become nearly horizontal a few miles southwest of the Mi Vida mine (1).

DESCRIPTIVE GEOLOGY

The ore zone in the Mi Vida mine ranges in thickness from a few feet to 23 feet. The sandstones are black to brown and commonly mottled or splotchy in appearance due to irregular replacement of calcite cement by ore

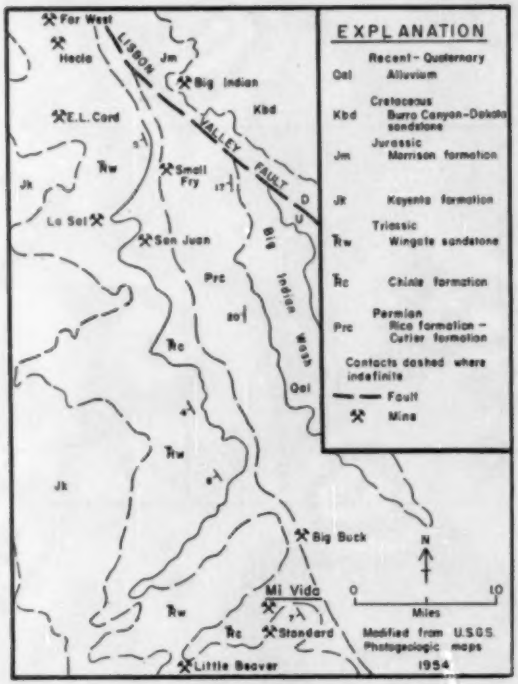

FIG. 2. Geologic map of Big Indian Wash, San Juan County, Utah.

minerals. Part of the ore zone is red-mottled, black calcareous sandstone which contains elongate black pods measuring one-half inch to two inches in diameter and several feet long. These pods are replacements of wood by uraninite and calcite. Many larger logs show only slight mineralization by calcite, pyrite, and galena. Variations in degree of replacement of carbonaceous material by ore minerals may have been due to variations in chemical state of the organic matter at the time of mineralization.

A few fairly consistent seams of greenish-gray mudstone occur within the

ore zone. The mudstone is highly fractured, containing slickensides, and a few fracture surfaces have a silvery, metallic coating containing molybdenum. Where concentrations of uraninite are greatest even the mudstone seams may be mineralized. Where the primary vanadium minerals are concentrated, secondary uranium vanadates may appear on the moist mine walls due to leaching along fractures. In general the roof is conglomeratic sandstone, and the floor is highly limonitic, calcareous sandstone.

MINERALOGY

Method of Study.—Thin and polished sections were examined for mineral determinations and textural relations of the uranium-vanadium ores. Etch tests were applied to individual ore minerals. Comparisons were made with known specimens of unoxidized ore from Club Mesa, Peanut, and La Sal No. 2 mines in order to recognize coffinite and V^{+4} oxide in polished section. These specimens were loaned by T. Botinelly and M. E. Thompson of the U. S. Geological Survey, Grand Junction. $FeCl_3$ etching darkens coffinite,

TABLE I

AVERAGE MINERAL COMPOSITION OF SAMPLES FROM BIG INDIAN WASH

	Big Indian Wash 61 Sections %	Mi Vida mine 39 Sections %	High Grade Ore 19 Sections %
Quartz	56	54	54
Feldspar	3	3	2
Calcite	28	22	16
Uranium and vanadium minerals, and vanadium clay	9	12	23
Clay	3	8	3
Accessories	1	1	2

thus distinguishing it from uraninite or carbonaceous material which remains unchanged.

X-ray and spectrographic analyses of coffinite and uraninite and UO_2/UO_3 analyses were made by the U. S. Geological Survey at Denver and Washington, respectively.

Those specimens containing V^{+4} oxide and coffinite were most susceptible to cracking due to dehydration. To prevent fracturing of polished sections, specimens were impregnated with epoxy resin prior to grinding.

Mineral Composition.—The general mineral composition of the ore and host sandstones is given in Table 1. The first column shows the major constituents of 61 thin sections which include core samples from two nearby claims and a few grab samples from the Big Indian Wash area in addition to specimens from Mi Vida. The second column is for 39 thin sections from the Mi Vida mine alone, and the third column is for 19 thin sections of high-grade ore from the Mi Vida mine.

Calcite decreases as uranium and vanadium minerals increase by replacement of the cement. Uranium concentrations do not coincide with vanadium

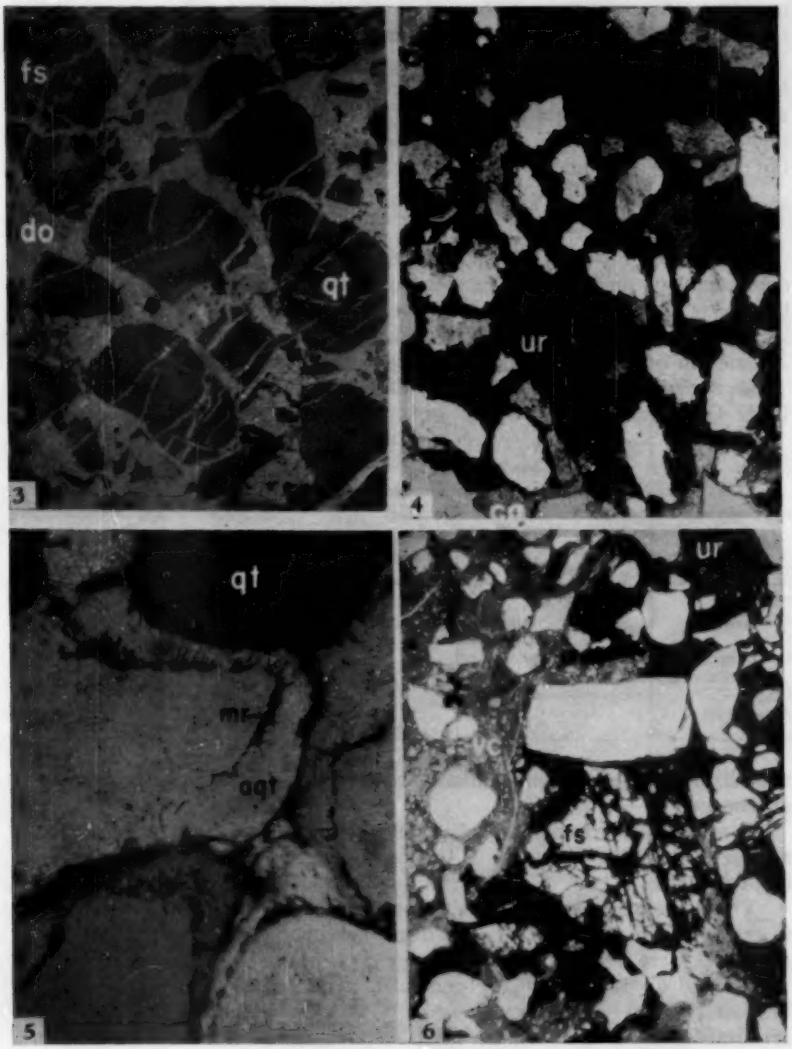

FIG. 3. V^{4+} oxide (do) veinlets in fractured quartz (qt) and feldspar (fs). × 85. Thin section.

FIG. 4. Scalloped quartz grains due to corrosion, uraninite (ur) and calcite (ca) cements. × 85. Thin section.

FIG. 5. Montroseite needles (mr) occurring along contact between quartz (qt) grains and authigenic silica overgrowths (aqt). × 170. Thin section.

FIG. 6. Sodic-calcic feldspar (fs) much fractured and replaced along cleavage directions by uraninite (ur); vanadium clay (vc) cement. × 85. Thin section.

concentrations (5). The same relation is recognized petrographically and is most pronounced where there has been replacement of carbonaceous material by uranium and vanadium minerals.

Non-metallic Minerals.—The chief constituents of the host rocks are quartz, feldspars, calcite, and vanadium clay. Quartz is the most abundant detrital mineral except in the calcarenites. Quartz grains in many samples have sutured borders. Some quartz is strained and fractured, especially in ore (Fig. 3). Quartz grains are commonly corroded by ore minerals (Fig. 4). Authigenic quartz overgrowths are common in some places, usually where ore concentrations are low, and presumably the low concentrations may be due to decreased permeability of the rock. Development of montroseite needles along the contact of detrital quartz with authigenic silica suggests that 1) the montroseite formed prior to the deposition of the secondary silica, or 2) the needles of montroseite were precipitated from vanadiferous solutions along the weak contact zone of the two ages of silica (Fig. 5). Gruner, Rosenzweig, and Smith (3) found that the montroseite needles penetrated the primary quartz as well as the secondary silica. The author believes that the montroseite is younger than the authigenic silica.

Plagioclase, ranging from albite to andesine, microcline, orthoclase, and perthite have been identified in the rocks of the Mi Vida mine. All feldspars are clastic grains. Microcline is less common than plagioclase in the thin sections examined. In most examples microcline grid twinning shows strain effects, but in samples containing ore microcline showed less corrosion and replacement along cleavage than plagioclase (Fig. 6). Perthite and orthoclase were scarce in the samples examined.

The principal cement in sandstones is calcite. In the calcarenites the calcite may comprise 70 percent of the rock because it occurs as both cement and detrital grains but in the calcareous sandstones it is about 25 percent of the total. Individual cement grains range from 0.03 to 5.0 mm in diameter, and the rock may show luster mottling where calcite occurs in large grains enclosing detrital materials. Calcite replaces plagioclase more readily than microcline. Carbonaceous material also is replaced by calcite, and recrystallized calcite fills desiccation cracks in the replaced wood.

Clay is an uncommon cement in Chinle sandstone, but is generally illite where present. Kaolinite and montmorillonite are rare. X-ray studies by J. W. Gruner show that the clay of mudstone lenses is mainly illite with minor amounts of montmorillonite (3). Sericite occurs as alteration of feldspar. Vanadium clay and metatyuyamunite, which are also cementing agents, are discussed under the heading "ore minerals."

Of the minor constituents, only the more prominent accessory minerals will be mentioned. In heavy mineral separations, apatite, barite, zircon, magnetite, and limonite appeared abundantly. Barite occurs in amber to yellow-brown tabular crystals ranging from a few millimeters to one centimeter in size. It is abundant in high-grade ore horizons, and also is present as cement in barren sandstone. In heavy mineral separations and in a few thin sections the barite is pleochroic in pale yellow. Zircon is common in all of the rocks except the calcarenites. Some crystals are cloudy, perhaps due

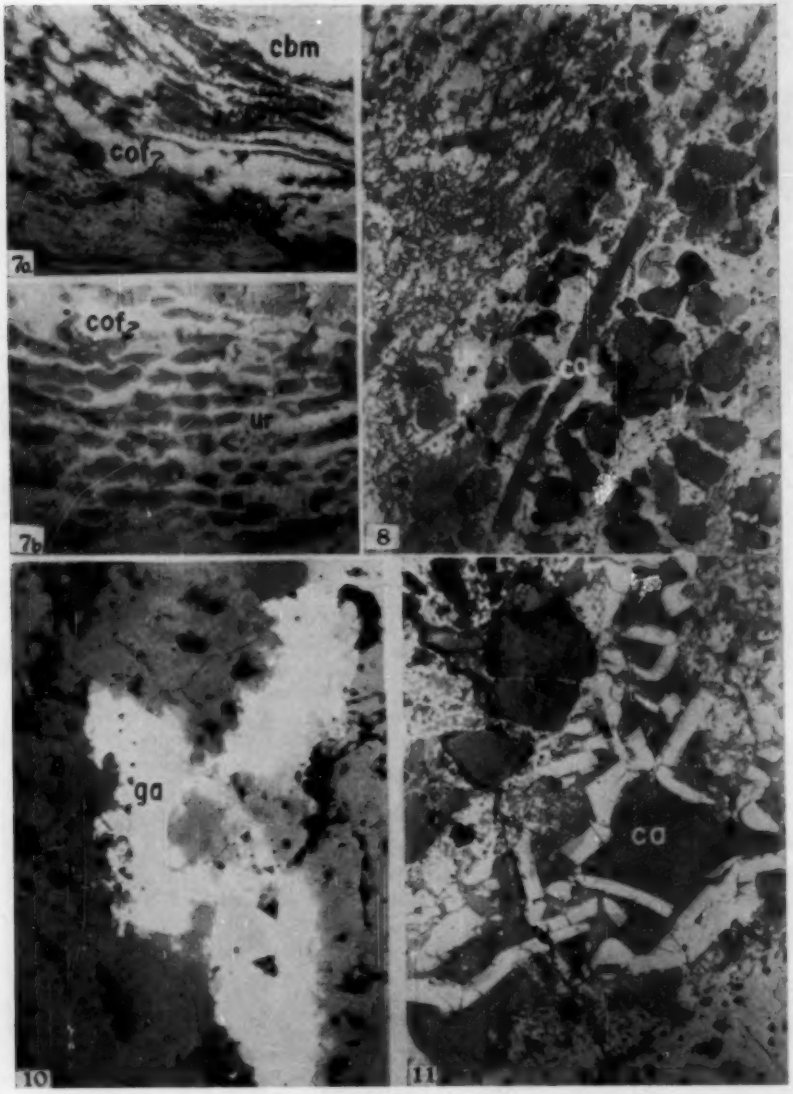

FIG. 7. Coffinite (cof) in cellular texture of replaced wood; etched with $FeCl_3$. × 300. Polished section.

a) Club Mesa mine, carbonaceous material (cbm) and coffinite (cof).

b) Mi Vida mine, uraninite (ur) and coffinite (cof).

FIG. 8. Uraninite (ur) cementing detrital grains adjacent to wood completely

to minute fracturing and abrasion in transportation. Muscovite is very common on bedding and lamenation planes. Red-brown biotite is fairly common, and in thin sections it is generally altered to a dirty brown color. Green tourmaline predominates over the blue. Garnets, magnetite, and rutile are minor components in the heavy mineral fractions.

Ore Minerals.—The uranium and vanadium ore minerals at Mi Vida occur as cement and as replacements. There are two black uranium minerals, coffinite and uraninite. Uraninite (UO_2 and lesser UO_3)[8] is common in portions of the ore zone which are high in carbonaceous material, associated with pyrite, montroseite, V^{+4} oxide, and calcite. Nearly all of the uraninite occurs as replacement of wood, but it also occurs as cementing mineral in sandstone, generally adjacent to carbonaceous material (Fig. 8). The uraninite occurring as cement is found in spheroidal blebs, and botryoidal and irregular masses. The spheroidal blebs range from 0.01 to 0.02 mm diameter, and massive material ranges up to several centimeters. Seams and small pods of uraninite replace carbonaceous debris. The specific gravity of the uraninite is 6.56 to 6.96. The chemical analysis by the U. S. Geological Survey is 47.40 percent UO_2, 29.15 percent UO_3, and 66.04 percent total U.

Coffinite $U(SiO_4)_{1-x}(OH)_{4x}$ occurs rarely in the mine, and is usually observed in shiny black, high-grade samples of wood replacement (6). It is associated with calcite, uraninite, and carbonaceous material. The paragenesis of coffinite is vague because of difficulty in recognizing it in polished section. Several samples from the Club Mesa and Mi Vida mines have been examined by X-ray and by etching polished surfaces with $FeCl_3$ (Fig. 7). A fairly pure specimen submitted to the U. S. Geological Survey had a variable specific gravity of 4.93 to 5.09. The chemical analyses indicated 31.62 percent UO_2, 41.67 percent UO_3, and 62.55 percent total U. Coffinite fills the cells in cellular structure of wood.

The Mi Vida ore contains five vanadium minerals. According to a report on one sample by Evans (2) the V_2O_5 content was 0.90 percent; and the Bureau of Mines reported in 1953 that the assays on five samples ranged from 0.15 to 6.40 percent V_2O_5 (5, p. 8).

The most abundant vanadium mineral is montroseite, VO(OH) or (V,Fe)O(OH). It is the least oxidized vanadium mineral of the deposit and is associated with uraninite, V^{+4} oxide, vanadium clay, and calcite. It occurs in the matrix of sandstones in bladed aggregates, rods and needles, ranging from 0.60 to 0.12 mm in length. As previously mentioned, mon-

[8] Throughout this report uraninite is used instead of the term pitchblende. X-ray examination shows an excellent uraninite pattern for the colloform uraninite. According to Dana's *System of Mineralogy*, 7th ed., vol. I, 1944, pitchblende is a massive, colloform variety of uraninite. The specific gravity of uraninite is 8 to 10, and of pitchblende less than 8.5, but lower specific gravity of the Mi Vida uraninite is due to included calcite and galena.

replaced by uraninite and calcite and also veined by calcite (ca). × 85. Polished section.

FIG. 10. Large crystals of galena (ga) replacing uraninite and calcite (gray). × 170. Polished section.

FIG. 11. Band of uraninite (light gray) fractured during minor deformation surrounded by later calcite (ca). × 85. Polished section.

troseite needles penetrate quartz and also occur along the contact between quartz and secondary quartz overgrowths (Fig. 5). In Figure 9 montroseite needles border the former outline of plagioclase that has been replaced by calcite, subsequent to the deposition of montroseite. The needles and blades are common in the cement replacing calcite and vanadium clay. Montroseite is abundant in the presence of uraninite in sandstone but is absent where wood is replaced by uraninite.

V^{+4} oxide, $V_2O_4 \cdot nH_2O$ (formula tentative), is present in the matrix of sandstones associated with uraninite, montroseite, and calcite (7). It takes a polish of steel gray color. Polarization colors are black, gray, greenish-

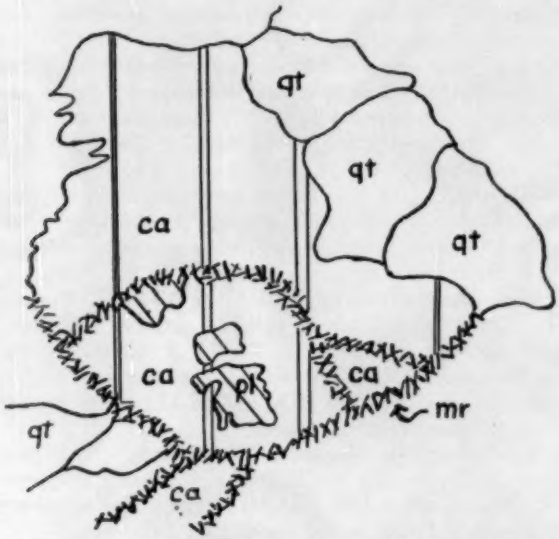

FIG. 9. Drawing illustrating the replacement of plagioclase (pl) by calcite (ca) with montroseite (mr) outlining original border of the plagioclase which was associated with quartz grains (qt). Not to scale.

cream, brown. V^{+4} oxide is translucent in very thin sections and is pleochroic from nearly colorless to straw yellow or deep yellow, or from orange-red to deep red. It occurs in radial feathery aggregates and plates less than 0.10 mm in length, which fill fractures in quartz and replace calcite cement. A pod in one specimen has a core of V^{+4} oxide surrounded by a band of fractured quartz with V^{+4} oxide matrix, and an outer rim of uraninite cementing quartz grains. The mineral relations suggest that V^{+4} oxide formed earlier than the uraninite. A complete mineralogic study of V^{+4} oxide is being made by L. R. Stieff and T. W. Stern, U. S. Geological Survey.

Blue-black secondary corvusite, $V_2O_4 \cdot 6V_2O_5 \cdot nH_2O(?)$, is present in the form of altered, granular aggregates in the matrix of sandstones in areas of

high vanadium concentration. It does not take a polish but when scratched leaves a green powder.

Pascoite, $Ca_2V_6O_{17}\cdot H_2O$, an orange colored secondary mineral, occurs in fractures and on damp mine walls in black sandstones in which vanadium minerals are abundant. In the Mi Vida mine it is unimportant as an ore mineral.

Vanadium clay [4] is the principal cementing material of the ore samples that contain much vanadium but little uranium. It occurs as brownish-green cryptocrystalline to microcrystalline fibrous, flaky, or granular aggregates. In thick sections or under low magnification the vanadium clay appears brown. It may contain included pyrite, greenockite, galena, montroseite, and uraninite. An examination of the vanadium clay under 430× to 950× magnification reveals rod-like grains two to three microns in diameter in a dense greenish matrix. Professor J. W. Gruner suggested that the rod-like forms may be vanadium bacteria; they appear to be similar to iron bacteria with which he is familiar (3). Structure in one specimen suggests that the vanadium clay was deposited in colloidal form, but the material generally appears to flow into the interstitial areas around detrital grains. The flow structure of the vanadium clay might indicate that mineralizing solutions corroded grains and simultaneously deposited vanadium clay while the solutions were in motion. Another possible explanation of the flowage structure is pressure from regional deformation, applied to the vanadium clay during or after ore deposition.

The only uranium-vanadate is metatyuyamunite, $Ca(UO_2)_2(VO_4)_2\cdot 5\text{–}7\ H_2O$. It is a secondary mineral occurring as a cement in the sandstone, replacing calcite, and also appearing in crystalline form as yellow to yellow-green coatings less than two millimeters thick on fracture surfaces.

Sulfides occur in close association with uranium-vanadium ores, and are especially common in wood replacement. Pyrite is most common, followed by galena and greenockite. The iron sulfide is present in the cement in minute intergrowths with uraninite, in irregular masses and blebs, and in bands or zones associated with carbonaceous material and calcite. Most of the galena is in bleb-like grains included in uraninite although some corroded euhedral crystals do occur, usually with calcite and uraninite (Fig. 10). Galena is observed with greenockite in desiccation cracks of replaced wood. Veins of galena and calcite fill fractures in uraninite. Sphalerite is a rare sulfide in the Mi Vida mine. It was observed by Gruner, Rosenzweig, and Smith (3) in small rounded grains only in one ore horizon, perhaps of detrital source, surrounded by clay minerals. The occurrence of chalcopyrite is similar to that of the sphalerite. In a polished thin section blebs of chalcopyrite occur in what appears to be a pebble, having a clay-like alteration rim. The pebble containing blebs of chalcopyrite probably was part of the original sedimentary deposit. Another section shows chalcopyrite in contact with

[4] In this report vanadium clay is a term used for a probable mixed layer montmorillonite-hydromica with substitution of vanadium in one or both lattices. This theory is suggested by a written communication from J. C. Hathaway, U. S. Geological Survey, who has made vanadium silicate studies of nearby Colorado Plateau clays.

pyrite and uraninite in replaced wood. Greenockite, a bright orange-yellow mineral, occurs as cement in sandstone associated with vanadium clay, galena, and pyrite. Some samples of replaced wood show greenockite and galena filling desiccation cracks. A few thin sections show greenockite in the clay matrix, in some cases surrounded by a clay alteration zone.

SEDIMENTARY TEXTURES

The range of average grain size diameter for all samples is 0.02 to 0.40 mm. The range of grain size for ore samples is from 0.08 to 0.30 mm. Generally, angular grains predominate. Finer grained sections contain more angular grains. In the calcarenites the limestone pellets are rounded and the matrix grains are angular to subangular. Size sorting of grains is generally poor, indicating rapid deposition, or nearby source rock and therefore possible nearby pinchout of strata. Lineation appeared in only a few specimens, generally those low in concentration of ore minerals and clastic carbonate. The structure is due chiefly to mica plates, in some cases to elongate plates of quartz and feldspar, in other cases to elongate or oval pellets of mudstone, siltstone, or limestone. Larger linear features are observed in the coarse and fine banding of the sandstone.

ORE TEXTURES AND STRUCTURES

The term "texture" is here used to describe the size, shape, and arrangement of mineral grains (4, p. 579). The textural features and associated structural conditions aid in understanding the character of the ore solutions and age relations of the minerals in the Mi Vida mine.

Detrital grains and cement have been fractured, presumably during tectonic deformation, which increased the permeability of the rocks. Subsequently the fractures have been healed by ore minerals and calcite. Post-ore minor fractures have also been healed by calcite.

In rocks containing abundant corvusite, detrital grains are extremely corroded but fracturing is limited. Specimens from low-grade ore zones show only slight fracturing and corrosion of grains. In the richer ore zones where V^{+4} oxide, montroseite, and uraninite, occur together, quartz and feldspar grains generally are much fractured (Fig. 3), and the calcite is strained and may be recrystallized. In many ore zones the alignment of the fracturing is random, but in some places the fractures are aligned across several detrital grains, indicating that the deformation has been post-cement but pre-ore (Fig. 3), although other evidence of fracturing of the calcite cement has been destroyed by recrystallization of calcite or replacement of calcite by ore minerals.

A post-ore stage of minor fracturing displaced bands of uraninite in a calcite matrix (Fig. 11), possibly due to post-ore tectonic deformation, resolution of calcite or pressure of recrystallization of calcite.

Transection Structures.—These structures, consisting of contact relations, metacrysts, and vein textures, are usually the most conclusive evidence

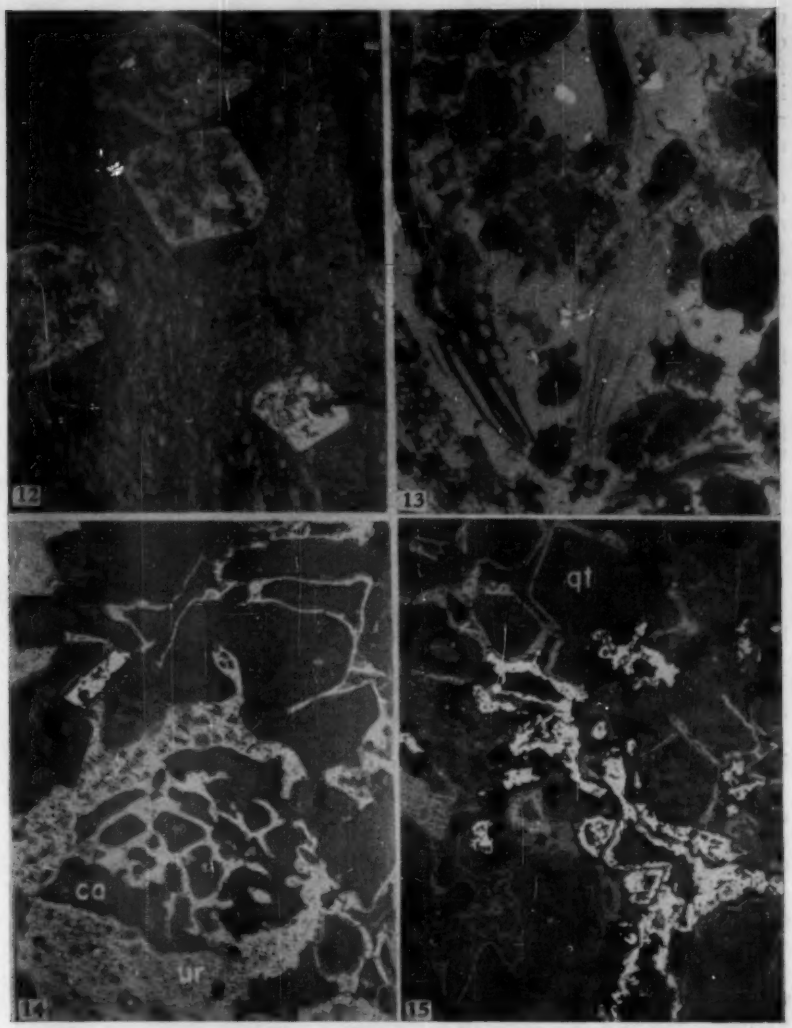

FIG. 12. Uraninite (light gray) pseudomorphs after pyrite (white) in a mudstone pebble. × 160. Polished section.

FIG. 13. Muscovite (dark gray) streaks replaced along (001) cleavage by uraninite (light gray). × 160. Polished section.

FIG. 14. Graphic replacement texture showing uraninite (ur) replacing calcite (ca). × 80. Polished section.

FIG. 15. Rim texture involving the replacement of calcite (ca) cement by pyrite (white) and uraninite (light gray) in sandstone with quartz (qt) grains. × 80. Polished section.

of age relations. In the specimens examined only uraninite, V^{+4} oxide, calcite, and galena, occur as veins. Calcite veins transecting uraninite are fairly common, but Figure 20 shows the rare reverse case of uraninite veinlets in calcite. Galena occurs in elongate masses in calcite veins, which indicates a later age than the uraninite but the same age as the vein calcite. Some vein development is a filling of desiccation cracks in replacement of wood.

Pseudomorphic Replacement.—Uraninite replaces the clay and minute detrital grains in mudstone pebbles to a minor extent, and uraninite pseudomorphs after pyrite are present in mudstone as skeletal crystal replacements where the ore minerals are concentrated (Fig. 12). Montroseite is found as pseudomorphs after calcite. V^{+4} oxide pseudomorphs after calcite occur in the center of a series of circular zones of a pod of replaced wood.

Guided Penetration Textures.—Bladed networks of montroseite often replace calcite along cleavage, and occasionally uraninite replaces feldspar grains (Fig. 6) and muscovite along cleavage (Fig. 13).

A pattern similar to graphic texture has resulted from penetration and replacement of calcite by uraninite (Fig. 14). Other types of guided penetration have resulted in network and rim textures produced by uraninite replacing calcite. In network development, spherical blebs of uraninite have formed linear aggregates. In rim textures uraninite has replaced calcite along the boundary between calcite and detrital grains as well as along cleavage planes. Pyrite also has developed a rim texture in a crude replacement of calcite (Fig. 15).

Island and Sea Texture.—Incomplete filling of a calcite druse by uraninite has produced an "island and sea" texture formed by calcite rhombs in uraninite (Fig. 16).

Colloform Texture.—Uraninite has been found in colloform development in replacement of carbonaceous material (Fig. 17). In other sections showing calcite replacing uraninite, remnant spherical blebs of uraninite are arranged in patterns suggestive of former colloform texture in the uraninite.

Cellular Texture.—Replacement of carbonaceous debris by calcite and uraninite is fairly common. Calcite occupies the cells and uraninite replaces the walls. There is a great variation in the character of the cellular texture. Cell sizes range from 0.03 to 0.08 mm. Some sections show the woody structure almost completely destroyed by uraninite; others show thick walls of uraninite with calcite-filled cells and also calcite filling the interstitial area outside the cell walls. In many places where calcite has filled the cell spaces, a thin selvage of uraninite outlines the cell walls (Fig. 18). The pellet forms or spherical aggregates of uraninite, where partly replacing calcite, show a scalloped contact (Fig. 19). In a few places cell walls have been replaced by uraninite and the cell interiors filled by vanadium clay. Rarely pyrite may be found occupying the cells of wood structure.

Cement Texture.—Pyrite, uraninite, V^{+4} oxide, montroseite, metatyuyamunite and vanadium clay are common cementing agents in the ore specimens. These minerals have partially replaced the calcite cement of the sandstones.

Miscellaneous Replacement Features.—Siltstone pebbles and fine granular calcite have been replaced by spherules of uraninite in many places. Lime-

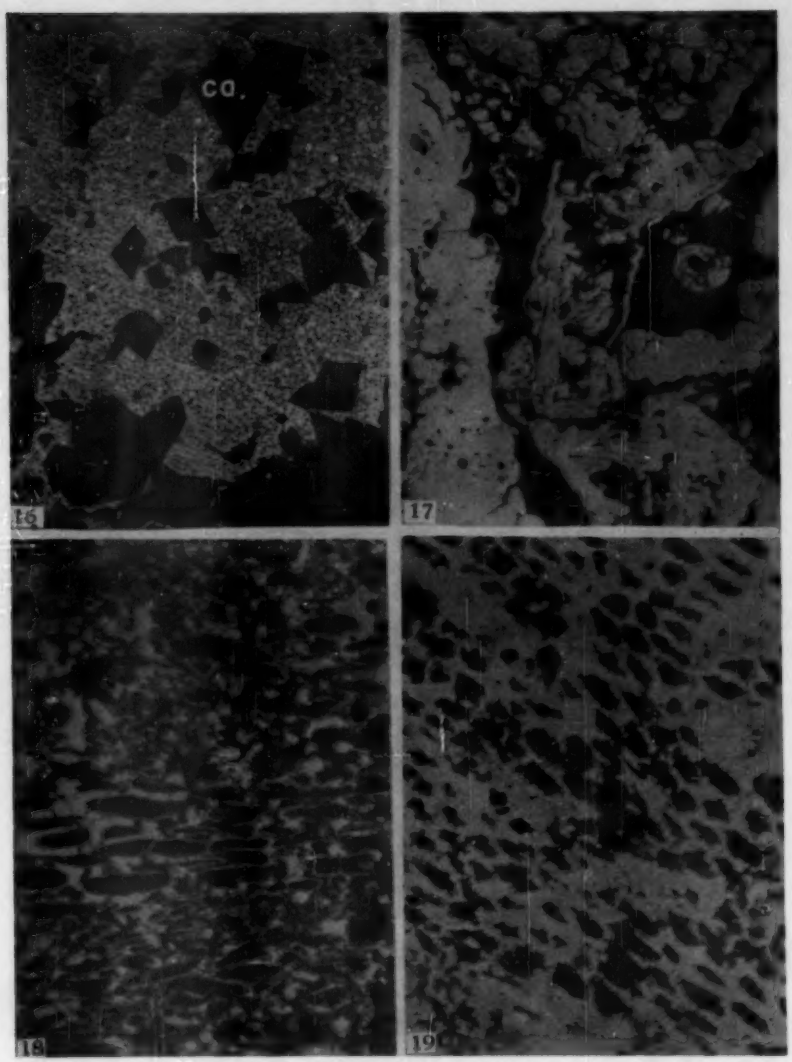

FIG. 16. Island and sea texture composed of rhombs of calcite (ca) in a fine granular mass of uraninite (light gray) and calcite (dark gray). × 80. Polished section.

FIG. 17. Colloform uraninite (light gray) replacing calcite (dark gray) in replacement of carbonaceous material. × 160. Polished section.

FIG. 18. Blebs and thin selvages of uraninite (light gray) partly replacing calcite (dark gray) in cellular structure of wood. × 300. Polished section.

FIG. 19. Cellular texture showing uraninite (light gray) producing a scalloped border in replacement of calcite (dark gray). × 160. Polished section.

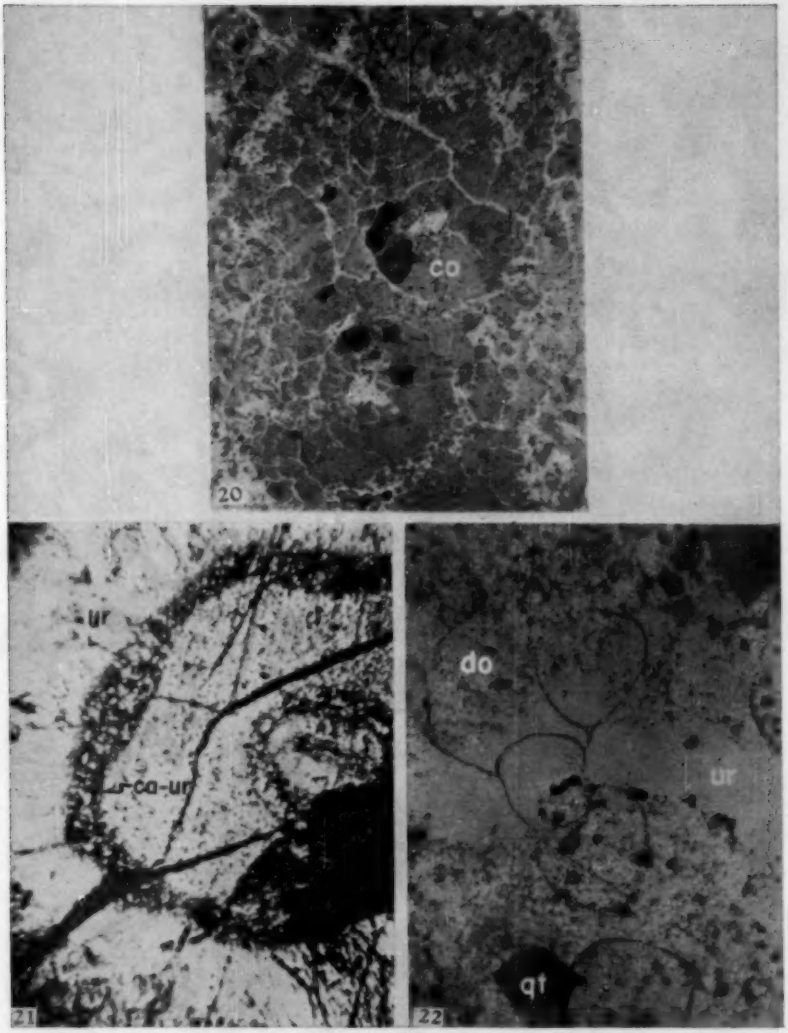

FIG. 20. Uraninite veinlets (white) transecting calcite (ca). × 80. Polished section.

FIG. 21. Zoning due to differential replacement of limestone pellet by uraninite (ur). × 18. Polished section.

FIG. 22. Nearly complete replacement of detrital grains by uraninite (ur) and V^{+4} oxide (do); only thin selvages of quartz (qt) remain. × 80. Polished section.

stone pellets in calcarenites adjacent to replacement of wood show zoning due to variations in original texture. Fine-grained calcite zones were replaced to lesser extent than coarse-grained zones, and central cores of coarse crystalline calcite are commonly completely replaced by uraninite (Fig. 21). Uniform textured limestone pellets are replaced completely by uraninite. Nearly complete uraninite replacement of detrital grains, perhaps limestone pellets and quartz, was seen in one section. Possibly silica solutions first penetrated the specimen and replaced the limestone pellets, but due to border impurities still retained the outline of the former grains. Uraninite and V^{+4} oxide were precipitated from ore solutions, replacing quartz except for a few minute selvages (Fig. 22).

PARAGENESIS

Detrital grains consisting of quartz, feldspars, micas, accessory minerals, rock fragments, and carbonaceous trash were deposited in late Triassic time and were cemented by authigenic silica, barite, calcite, or clay (Fig. 23).

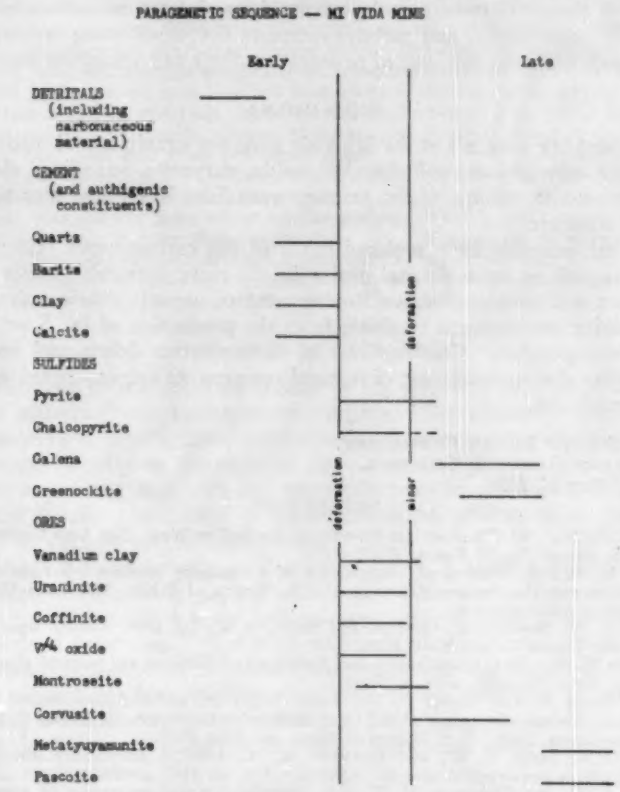

FIG. 23. Paragenesis of uranium mineralization at the Mi Vida mine.

Later fracturing of quartz and feldspar (Fig. 3) and recrystallization of some calcite may have been associated with folding and faulting. Vanadium clay, coffinite, uraninite, montroseite, and V^{+4} oxide replaced carbonaceous trash and calcite cement, and, in a few cases, detrital grains. Uraninite selectively replaced pyrite in mudstone pellets, calcite in limestone pellets, and carbonaceous material. Coffinite formed only in replacement of carbonaceous debris. Montroseite and vanadium clay were precipitated in great quantities in the sandstone interstices, but only to a minor extent in carbonaceous material. Montroseite developed at a slightly later stage than the uraninite. Pyrite was introduced at the time of uraninite and V^{+4} oxide. Chalcopyrite also was early in the sequence, but its age relations to pyrite and uraninite could not be determined in replaced wood. Subsequent minor local deformation resulted in recrystallization of calcite and breakup of some of the uraninite bands (Fig. 11). Galena and greenockite were deposited after the minor local deformation, principally in desiccation cracks in carbonized wood.

The primary ore minerals were oxidized much later, perhaps in Pleistocene or Recent time. Corvusite and pascoite formed from vanadium minerals, principally montroseite, and metatyuyamunite developed along fractures and open spaces left from leaching of primary uranium and vanadium material.

CONCLUSIONS

Principal ore minerals at the Mi Vida mine are uraninite and montroseite. Minor ore minerals are coffinite, V^{+4} oxide, corvusite, vanadium clay, and metatyuyamunite. Some of the primary vanadium is slightly later than the primary uranium.

The ore minerals have replaced much of the carbonaceous material and cement as well as some detrital grains in the more permeable lower Chinle sandstones and conglomerates. Replacement of organic debris may be due to a reducing environment resulting from the production of H_2S or H_2SO_3 in its decomposition. Combinations of carbonaceous debris and increased permeability due to fracturing of mineral components are associated with the highest grade ore.

U. S. Atomic Energy Commission,
Grand Junction, Colorado,
May 21, 1956

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IS ANTHRAXOLITE RELATED GENETICALLY TO COAL OR TO OIL?

R. V. DIETRICH

ABSTRACT

Anthraxolite is the name commonly given to anthracite-like materials that occur in veins and as disseminated masses in sedimentary rocks. Despite the fact that no genetic relationships between anthraxolite and oil have been proved to be universal, discoveries of anthraxolite nearly always initiate special interest because it is believed that they may indicate the presence of nearby oil.

The primary objective of this investigation has been to determine if there could be found in the laboratory a means of establishing a consanguinity between anthraxolite and similar natural high-carbon compounds, whose occurrences permit more than one interpretation of origin, and coal or between these same substances and oil. Ash content analyses and thermal, x-ray diffraction, "glow point," and spectrographic data obtained from anthraxolite samples from numerous localities have been compared to those same data obtained from coals of diverse ranks, lignite, numerous asphaltic materials, paraffin- and asphalt-base oils, heavy petroleum residues, quisqueite, natural graphite, and graphite powders derived from coal coke and from petroleum coke.

Three conclusions have been reached: 1) anthraxolite with an ash content of less than two or three percent probably, although not necessarily, was derived from oil or oil-like material(s); 2) anthraxolite with an ash content of more than two or three percent, unless its occurrence is definitive, could be consanguineous with either coal or oil; and 3) no way has been found to establish a genetic relationship between anthraxolite and coal versus oil by the other methods investigated.

INTRODUCTION

THIS investigation was initiated because of the discovery in 1953 of an occurrence of anthraxolite in southwestern Virginia. The discovery renewed special interest in oil production possibilities in the area because of the structure of the rocks underlying the material and because of the fact that geologists who are acquainted best with the many problems involved still believe that there are definite possibilities of future increased production in the Appalachians of Virginia and adjacent states.

An answer to an inquiry by the writer of R. S. Young (personal communication, 1954), "I do think, with reservation, that *x*-ray analysis can be used to distinguish between hydrocarbons derived from petroleum versus those derived from coal," prompted inclusion of *x*-ray analyses in the investigation. It should be mentioned with regard to this aspect of the study that no attempt has been made to determine actual structures of the diverse materials; it was known at the outset that Dr. Young planned to extend his work to do this so the materials considered here were made available to him for such investigation.

ACKNOWLEDGMENTS

Nearly all of the samples and some of the analyses of the investigated materials were furnished to the writer by others (Table 1). Charles E. Sears, Jr. of the VPI Department of Geological Sciences prepared the tracings of the *x*-ray patterns and D.T.A. curves. Charles T. Holland and Carl Shelton of the VPI Mining Engineering Department, Robert C. Krug of the VPI Chemistry Department, and Byron N. Cooper and Wallace D. Lowry of the VPI Department of Geological Sciences discussed certain aspects of the involved problems with the writer. Maurice Deul of the U. S. Geological Survey criticized the original manuscript. All of this aid is acknowledged gratefully.

PREVIOUS WORK

Chapman (3, p. 143) proposed the term anthraxolite for anthracite-like materials occurring in veins and as disseminated masses in sedimentary rocks and believed to be a ". . . product of alteration from petroleum or asphalt. . . ." He noted many Canadian occurrences. Rutherford (17) listed, in a summary, numerous other occurrences of similar materials in Canada. Dunn (6) has suggested that a black carbonaceous material that occurs in Central New York and was called "anthracite" by Vanuxem (21) as well as Inostranzeff's (12) "schungite" is similar to anthraxolite; he so named the New York material.

The only workers who have published ideas concening possible genetic relationships between anthraxolite and coal or petroleum are Kelly (13) and Dunn (6). Kelly (*op cit.*, p. 47), using the procedure described by Turner and Randall (20), concluded that "Although there are points still to be elucidated in the microscopical study of anthraxolite, the evidence thus far produced seems to prove that woody tissue does not play a part in the origin of anthraxolite, which differs in this respect from ordinary anthracite"—the anthraxolite considered in Kelly's investigation was from Sudbury, Ontario. Dunn (*op. cit.*, p. 489), in his paper concerning the Mohawk Valley, New York, material, suggested that "It was originally a liquid, which became concentrated in zones of relatively high porosity and permeability in a manner similar to petroleum. Having first saturated the carbonate strata, it underwent subsequent changes which produced a decrease in volume and a corresponding increase in viscosity until it attained its present solid brittle condition . . . and . . . The parent material was probably vegetable and conceivably the algal reefs and biostromes of *Cryptozoon* in the Little Falls dolomite may have been the source."

None of the numerous reports of laboratory investigations of high-carbon solids have included data on anthraxolite. A few examples of such studies may be listed: *x*-ray—Krishnimurti (14), Riley (16), Franklin (7), Siever (19) and Young and Robertson (22); differential thermal—Glass (9) and Clegg (4); "glow point"—Arms (1).

OCCURRENCE

The anthraxolite, the discovery of which initiated this investigation, is black, has a vitreous to oily luster, is brittle, breaks with a subconchoidal

fracture, has a hardness of 2 to 3, a specific gravity of 1.53 ± .01, and is what generally would be termed infusible. An analysis on an ash-free basis (weight percent) of the material gives C—93.31, H—2.32, N—0.89, O—2.95 (by difference), and S—0.53 (Commercial Testing and Engineering Co. analyst). It occurs as irregularly shaped, poorly laminated fragments, up to four inches in greatest dimension, in the thin residuum and in the colluvium about 25 and 200 feet, respectively, north of Calhoun Run, approximately one-half mile east of Alleghany Springs in southeastern Montgomery County, southwestern Virginia. The bedrock directly beneath the anthraxolite-bearing residuum is a steeply-dipping, slightly-brecciated, vuggy, saccharoidal, black dolomite member of the middle (or lower?) Cambrian Rome formation. Breccia that appears to be associated with a minor cross fault within the Rome formation appears to be the source of the anthraxolite-bearing colluvium. Although no anthraxolite has been found to occur within the underlying dolomite or within the fault breccia, it appears that it must have been within one or the other or both of these units. Adjacent rocks consist mainly of compact siltstones and shales.

Although it was impossible to show that this anthraxolite gained its position by flowing into the host(s), the occurrence immediately appeared to be of particular interest with regard to the possibility that it might indicate oil at depth. Dolomite(s) of the same lithology as that with which the anthraxolite is associated and adjacent rocks, along with breccias, comprise zones and units in the Rome formation through which fluids are known to have flowed with facility—they are the loci of hydrothermal mineralization, *e.g.*, the Bonys Run sphalerite-galena deposit. Further, so far as significance concerning possible petroleum occurrence at depth, the Rome formation of the area is believed possibly to constitute part of a thrust sheet—possibly a folded thrust (5)—and the age and lithology of the rocks underlying the Rome at the locality are unknown.

LABORATORY INVESTIGATIONS

In the attempt to determine possible consanguinity between the Calhoun Run anthraxolite and petroleum versus coal (and, it should be added, perhaps, that the possibilities that the material could have been the result of hydrothermal actions or the result of the breakdown of carbonates in association with some geologic phenomenon, such as faulting, have been ignored), the first step was to procure samples of numerous high-carbon substances of diverse origins. The materials obtained are listed (Table 1).

As can be seen, the main objective was to include not only many diverse materials but to include similar materials of different genetic relationships.

The only methods of analysis employed in the investigation were those readily available in most geological laboratories and thus familiar to most geologists—even to those who have had no specialized training in organic chemistry. Ash content was determined for those materials for which the figure was not supplied; all samples were submitted to *x*-ray diffraction investigations; most of the anthraxolite, the coals, the impsonite, and the petroleum residues were submitted to differential thermal analyses; "glow points" were determined for some of the anthraxolites, for many of the coals,

and for impsonite; most of the samples and the ashes produced by burning some of them were submitted to spectrographic analysis.

Each sample of solid material was ground with an agate mortar and pestle to − 100 mesh before ash determinations and differential thermal analyses were made, and to − 300 mesh before being submitted to *x*-ray diffraction

TABLE 1

MATERIALS INCLUDED IN THIS INVESTIGATION*

Name	Locality	Remarks
anthraxolite	Calhoun Run, Montgomery Co., Va.	in residuum and colluvium above middle (lower?) Cambrian Rome fm., complete description this paper.
anthraxolite	Flat Creek, near Sprakers, N. Y.	in pockets in lower Ordovician Little Falls dolomite; (James R. Dunn).
anthraxolite	Balfour Twp., Algoma Dist., Ont.	(W. M. Tovell), The Royal Ontario Museum No. E-1314.
anthraxolite	Chelmsford, Ontario	(W. M. Tovell), The Royal Ontario Museum No. M-13385.
anthraxolite	Lot 4, Concession 2, Balfour Twp., near Sudbury, Ontario	(W. M. Tovell), provided by W. M. Moorhouse of the Univ. of Toronto; this and preceding two materials ". . . probably are from the same general locality, and perhaps even from the same vein" (W. M. Tovell, personal communication).
anthraxolite	Cochenour-Williams Mine, Red Lake, Ont.	(W. M. Tovell), The Royal Ontario Museum No. M-21203 (from a gold-bearing vein).
anthraxolite	near Kingston, Ontario	with barite in vein in middle Ordovician Black River limestone; (W. M. Tovell), The Royal Ontario Museum No. M-19999.
anthraxolite	Port Arthur, Ontario	(W. M. Tovell), The Royal Ontario Museum No. M-11632.
anthraxolite	Rossport, Thunder Bay Dist., Ont.	(W. M. Tovell), The Royal Ontario Museum No. M-9965.
"anthraxolite"	South Shore Great Slave Lake, N.W.T.	in vugs in Upper Devonian; (W. M. Tovell), provided by W. M. Moorhouse.
"rock asphalt"	near Mammoth Cave, Edmonson Co., Ky.	four samples from lower Pennsylvania (Pottsville) sandstone; one sample from Mississippian Big Clifty sandstone; (Preston McGrain).
asphaltic sandstone	SW¼SE¼ sec. 15, T.1S., R.3E., Murray Co., Okla.	from Ordovician Oil Creek formation; (W. E. Ham).
"asphaltic matter"	Ione, Amador Co., Calif.	from Type 16 Wax—Lignite to Montan Wax process; (F. J. DeAngelis), who notes (personal communication) ". . . true asphaltic derivatives, or high melting point colored hydrocarbons, polymerized contaminants, or perhaps cellulose or semi-cellulose contaminants. . . ."
"asphaltic matter"	Ione, Amador Co., Calif.	from Type 16 Wax—"Bottoms DP1–4112"—As above.
asphaltic (?) residue	Hagan, Lee Co., Va.	in lenticular cavity in mid-Ordovician Hermitage limestone; U.S.G.S. worker(s) reported material to contain Pennsylvanian plant spores; (B. N. Cooper); found by J. E. Sanders.
asphaltic (?) residue	South of crest of Moccasin Ridge, Russell Co., Va.	partially fills vugs (lined with dolomite crystals) in upper Cambrian Copper Ridge dolomite; (W. D. Lowry).
anthracite coal	Lehigh Valley, Pa.	from lower Pennsylvanian (Pottsville); five samples: one each from Lower Baltimore, Bowkley, Hillman, Mammoth, and Wharton seams; (H. B. Wiekey).
semi-anthracite	Price Mt., near Blacksburg, Va.	from lower Mississippian Price fm. (Merrimac seam); three samples: "run of the mine," 2½ in. lump—1.65 ± .05 S.G.; 2½ in. lump—1.40 ± .03 S.G.; (M. P. Corriveau).
low-volatile bituminous	Coalwood, West Virginia	from lower Pennsylvanian (Pottsville) Pocahontas No. 3 seam; two samples; (H. E. Mauck).
high-volatile bituminous	Fairmont, West Virginia	from Pennsylvanian (Monongahela) Pittsburgh seam; two samples; (G. L. Judy).
cannel coal	Holden, West Virginia	from lower Pennsylvanian (Pottsville) Cedar Grove seam of Kanawha group; (A. J. Bartlett).

* Names in parentheses indicate the supplier.

TABLE 1—*Continued*

MATERIALS INCLUDED IN THIS INVESTIGATION*

Name	Locality	Remarks
crude oil	Bradford field, Pa.	paraffin-base; from Devonian strata; (C. M. McKinney).
crude oil	Sunset field, San Joaquin Valley, Calif.	naphthene- or asphalt-base oil; from upper Miocene or Pliocene strata; (C. M. McKinney).
gilsonite	Foxen Canyon, near Sisquoc, Santa Barbara Co., Calif.	from Miocene Monterey shale; (C. W. Jennings).
gilsonite	Uinta Basin, about 20 mi. SE of Vernal, Utah	from Eureka vein; termed "L grade"; (P. L. Morse).
gilsonite	Uinta Basin, about 20 mi. SE of Vernal, Utah	from Bonanza vein; termed "VB grade"; (P. L. Morse).
graphite	Columbo Mines, Ceylon	"platy" type from fissure vein; from one of world's most productive deposits of high-grade graphite.
graphite	near Adney Gap, Franklin Co., Va.	similar to so-called "amorphous graphites"; in pods in an augen gneiss.
graphite powder	———	"Acheson" graphite powder "38-P2"; from petroleum coke; (J. G. McMahon).
graphite powder	———	"Acheson" graphite powder "AF-1"; from coal coke; (J. G. McMahon).
impsonite	NE¼SE¼ sec. 23, T.3N., R.25E., LeFlore Co., Okla.	from Carboniferous Jackfork sandstone; originally called "grahamite"; (W. E. Ham).
lignite	Ione, Amador Co., Calif.	from middle Eocene Ione formation; (F. J. DeAngelis).
montan wax	Ione, Amador Co., Calif.	"type 16" derived from above lignite; in preparation of this, lignite has been subjected to actions of petroleum solvents—supposedly all solvents have been subsequently removed; (F. J. DeAngelis).
petroleum residuum	Anahuac salt dome field, south of Houston, Texas	vacuum residuum, cut point—1220, 3.0 percent on crude; mixed base crude—Upper Oligocene; (Esso Res. & Eng. Co.).
petroleum residuum	Bachaquero—Maracaibo Lake area of western Venezuela	vacuum residuum, cut point—1175, 31.0 percent on crude; asphaltic base crude—lower Miocene; (Esso Res. & Eng. Co.).
petroleum residuum	Baxterville field, Lamar Co., Miss.	residuum from which all compounds boiling below 400° F have been removed; asphaltic base crude—lower Cretaceous, Tuscaloosa fm.; (Gulf Res. & Dvlpmt. Co.).
petroleum residuum	Baxterville field, Lamar Co., Miss.	vacuum residuum from which all compounds boiling up to 1,000° F. have been removed; asphaltic base crude—lower Cretaceous, Tuscaloosa fm.; (Gulf Res. & Dvlpmt. Co.).
petroleum residuum	San Joaquin Field, Venezuela	vacuum residuum, cut point—1230, 3.6 percent on crude; paraffinic base crude—middle Miocene; (Esso Res. & Eng. Co.).
petroleum residuum	Southern Louisiana	vacuum residuum, cut point—1250, 1.7 percent on crude; paraffinic base crude—Miocene; (Esso Res. & Eng. Co.).
petroleum residuum	Tia Juana—Maracaibo Lake area of western Venezuela	vacuum residuum, cut point—1250, 14 (est.) percent on crude; asphaltic base crude—lower Miocene; (Esso Res. & Eng. Co.).
petroleum residuum	West Texas	vacuum residuum, cut point—1250, 3.5 (est.) percent on crude; mixed base crude—lower Permian; (Esso Res. & Eng. Co.).
petroleum residuum	none given	residuum from which all compounds boiling below about 600° F have been removed; paraffinic base crude; (Gulf Res. & Dvlpmt. Co.).
quisqueite	Minasragra, Peru	from vanadium ore of area.

* Names in parentheses indicate the supplier.

and numerous other tests. The asphaltic portions of the rock asphalts were separated from their host materials by pulverizing the rocks in a Raymond Mill and then placing an aqueous pulp of the pulverized materials into a 50 gram Deco flotation cell. The air bubbles introduced into the pulp caused levitation of the desired fractions.

Numerous x-ray setups, including a General Electric XRD–3 diffraction unit with a No. 1SPG spectrogoniometer, and a Westinghouse unit with 114.6 mm and 57.3 mm cameras were used. CuKα radiation with a Ni filter and

CoKα radiation with an Fe filter were used with the XRD–3 unit; CuKα radiation with a Ni foil filter were used with the Westinghouse unit. Numerous types of samples were submitted to diffraction in each of the setups before a "standard" method was decided upon. It was found that patterns obtained from CoKα radiation (with the XRD–3 unit) on finely ground powder ($-$ 300 mesh) that was allowed to sediment from a slurry on an etched glass slide gave the most definitive results for the solids. The heavy petroleum residues gave best results when they were melted in a low heat on a glass slide and the resulting fluid was allowed to cool to a high viscosity. The highly fluid oils were submitted to diffraction in many different types of sample holders with nearly equal results—for example, they were put on the etched slides and held at relatively low temperatures so that their viscosity

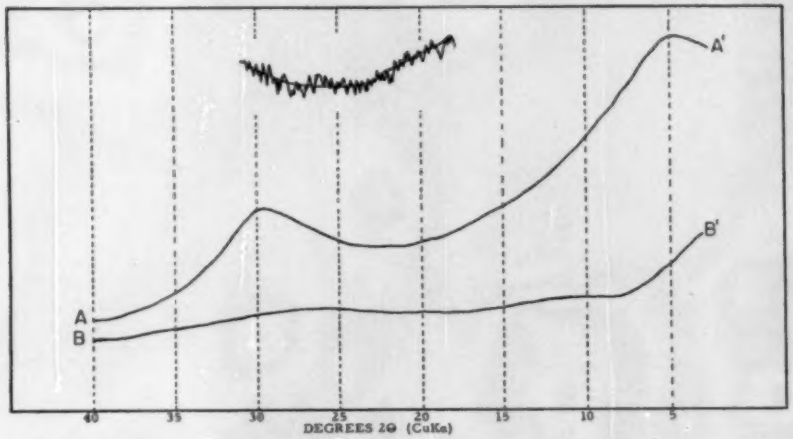

FIG. 1. Tracings of x-ray pattern from anthraxolite (A $-$ A′) and from blank slide (B $-$ B′); insert in upper center indicates method used to prepare the tracings presented as figures in this paper—highly irregular line is actual tracing.

increased to the point that at least a film of them remained on the slide throughout the x-ray traverse, they were submitted to the x-rays under an arrangement whereby a steady supply of oil flowed over the slides throughout the traverse, and they were allowed to permeate ceramic blocks which were submitted to x-ray diffraction after which the peaks derived from reflections from the ceramic materials were subtracted from the complete patterns.

After all materials were submitted to x-ray analysis, most of the anthraxolites, anthracite, semi-anthracite, low-volatile and high-volatile bituminous, impsonite, the Virginia "asphalt residua," and the heavy petroleum residua were submitted to differential thermal analysis. The materials were ground to $-$ 100 mesh and were tight-packed (4, p. 10). The differential thermal setup used was an FH305 furnace in vertical position with an x-y recorder

attached to a three point Pt-Pt-10Rh wire thermocouple system. A heating rate of approximately 12½° C/min. was used between 50 and 1000° C.

"Glow points" were measured for some of the coals, for the impsonite, and for some of the anthraxolites according to the method outlined by Arms (1).

The Virginia anthraxolite was sectioned, polished and submitted to microscopic examination before and after chromic acid and heat etching.

Ash content was determined by the coal method.

RESULTS

X-ray Analyses.—The materials investigated may be placed into eight, and possibly nine, categories on the basis of their x-ray diffraction patterns (Figs. 2 and 3):

I. The natural graphites and the graphites produced from coal and petroleum cokes gave essentially typical graphite patterns. At 2θ angles of less than those that give d values of more than 3.30Å, which appears to include the critical peaks[1] of the materials considered, the patterns for all of the graphites show a sharp, high intensity peak with d value of approximately 3.39Å, a broad, lower intensity peak with its highest value with a d value of approximately 6.90Å, and a broad, even lower-intensity peak with its highest point with a d value of about 16.28Å. The smaller, sharp peak (Fig. 2) is the kβ of the 3.39Å peak. The x-ray patterns of the graphites derived from the cokes differ from those of the natural graphites in that their low-angle broad peak is less intense.

II. The anthraxolites from Virginia, from New York, and from Chelmsford and Kingston, Ontario, the anthracite coals, the semi-anthracite coals, the low-volatile bituminous coals, the impsonite, and the "asphalt (?) residua" from Virginia all gave patterns characterized by a low-angle intensity maximum and a broad peak with its highest point at approximately $d = 3.55$Å. The high-volatile bituminous coal gave patterns that may be of this category but definition of these patterns is not sufficient to place them in this group without reservations. The anthraxolites and anthracite coals also gave a series of minor peaks in the region between $d = 2.25$Å and $d = 2.01$Å. The Chelmsford, Ontario anthraxolite gave the modification indicated by the dashed line with highest intensity at $d =$ approximately 9.22Å.

IIa. The two anthraxolites from Balfour Township, Ontario, the anthraxolite from Rossport, Ontario, and the anthraxolite from Port Arthur, Ontario, gave patterns that appear to be a combination of the pattern given by the materials listed in the preceding category (II) and the main graphite peak (Fig. 2). All but the Port Arthur material gave the dashed line modification.

III. The quisqueite and the anthraxolite from Red Lake, Ontario, gave patterns that also may be related to the graphite pattern and the pattern given by materials in category II. Each has a questionable low-angle maximum,

[1] The term peak is used in this report, rather than "halo," "ring," or the like because peaks are actually what are observed on the patterns produced by the x-ray setup used.

a broad peak with highest intensity at approximately $d = 8.22$Å, and a moderate-intensity sharp peak in the position of the main graphite peak, *i.e.*, $d =$ approximately 3.39Å.

IV. The asphalts from the Kentucky Rock Asphalt samples and from the Oklahoma Asphaltic sandstone, the California lignite, and the cannel coal gave patterns with a broad peak extending between $d = 12.82$Å and 5.88Å

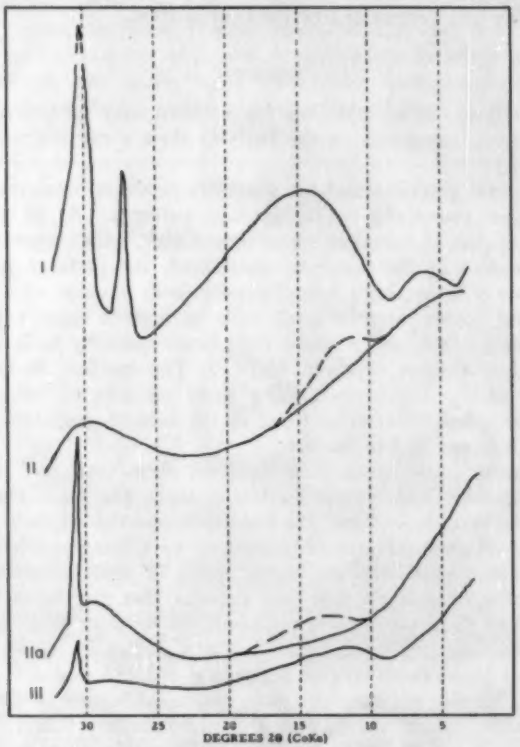

FIG. 2. Tracings of x-ray patterns given by substances in categories I, II, IIa, and III.

with a sharp, superposed peak with its maximum having a d value of approximately 7.14Å.

V. The Montan Wax, Type 16, and the San Joaquin residuum gave patterns characterized by two sharp peaks, the one with the lower d value having the lower intensity, plus a broad low-intensity peak. The d values for these are approximately 4.12Å and 9.33Å, respectively. The Montan Wax, which was ground to -300 mesh and allowed to sediment on a slide from a slurry, gave the curve indicated by the solid line whereas the petroleum resi-

due, the sample of which was prepared by melting and subsequent cooling to a near solid state on a slide, gave the dashed-line modification in the low 2θ area.

VI. The asphaltic materials from the Montan Wax gave patterns with a low-angle intensity maximum and a peak with a d value of approximately 4.13Å.

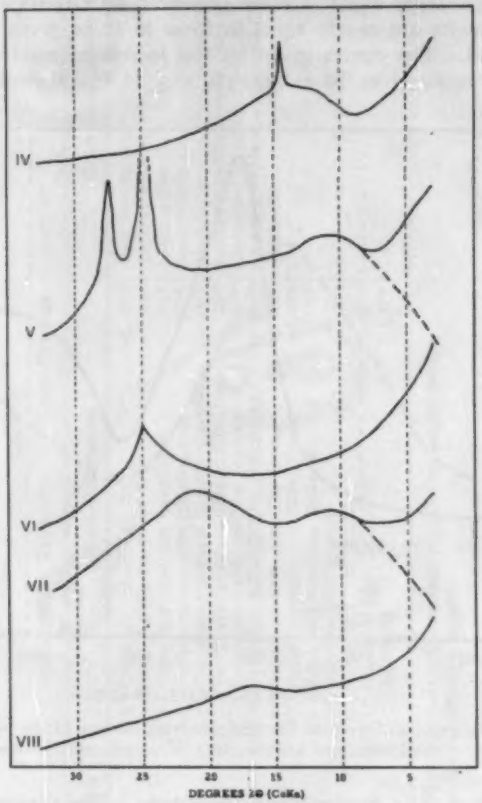

FIG. 3. Tracings of x-ray patterns given by substances in categories IV, V, VI, VII, VIII.

VII. The petroleum residua (other than that obtained from the San Joaquin crude) gave two broad, low-intensity peaks, one with its highest point at approximately 9.00Å and the other with its highest point at approximately 4.90Å. As in category V, the ground samples gave the solid line curve and the melted and subsequently cooled samples gave the dashed line modification in the low 2θ area.

VIII. The California and Utah gilsonites gave patterns with a questionable broad peak with its greatest intensity at d = approximately 6.12Å. The crude oils also appear to be of this category. Strictly speaking, however, the designation of any part of the patterns derived from the oils as a "peak" is extremely subjective.

Differential Thermal Analyses.—Differential thermal analyses of the coals gave curves essentially equal to those presented by Glass (9). The curves given by impsonite are nearly equal in form to those given by low-volatile bituminous coal. The curves given by the petroleum residua were diverse and indicated as many as 10 exothermic and 11 endothermic reactions be-

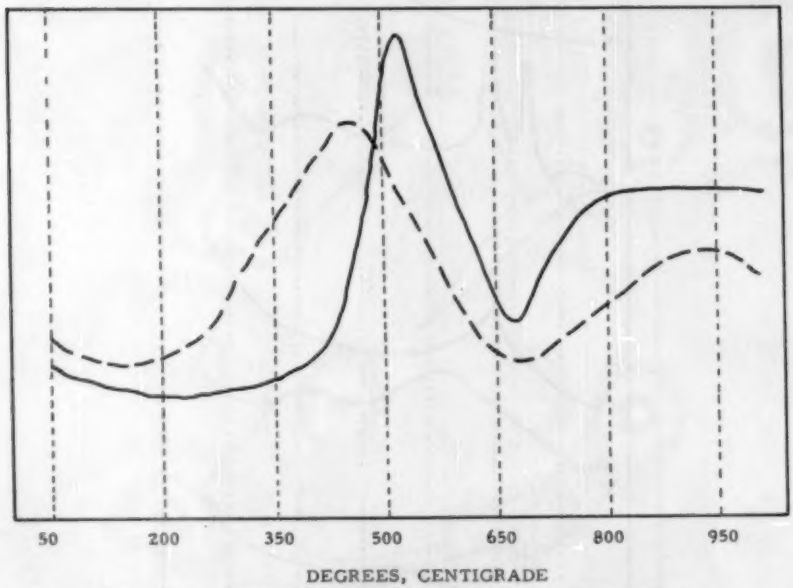

FIG. 4. Tracings of differential thermal analysis curves given by anthraxolite (Virginia)—solid line, and anthracite (Wharton seam)—dashed line.

tween 50° C and their combustion temperature. The curves from the anthraxolites from Virginia, New York, and those from Ontario for which sufficient samples were available gave curves nearly identical in form to the curves given by anthracite and semi-anthracite coals. The curves are characterized (Fig. 4) by a low temperature exothermic reaction which represents loss of moisture, an exothermic reaction which has escaped correlation with any certain process(es) to the present time, and a high temperature endothermic reaction which apparently represents loss of volatiles. The only notable difference between the anthraxolite curves and those given by the anthracite coals is that the exothermic reaction occurs between 480° and

TABLE 2

ASH CONTENT, EXPRESSED IN WEIGHT PERCENT, OF SAMPLES

Coal and coal derivatives		Oil and oil derivatives		Substances of unknown derivation	
Anthracite (Baltimore)	8.3	Crude oil (Bradford)	< .01*	Anthraxolite (Va.)	<2.14*√
Anthracite (Bowkley)	5.9	Crude oil (Sunset)	< .01*	Anthraxolite (N. Y.)	.28*
Anthracite (Hillman)	10.5	Petroleum residuum (Anahuac)	< .01*	Anthraxolite (Kingston, Ont.)	1.15*√
Anthracite (Mammoth)	5.4	Petroleum residuum (Bachequero)	.37*	Anthraxolite (Sudbury, Ont.)	1.56*
Anthracite (Wharton)	9.9	Petroleum residuum (Baxterville-400)	< .01*	Asphaltic matter (from montan wax process)	1.25*
Semi-anthracite (S.G.-1.65)	25	Petroleum residuum (Baxterville-1000)	.10*	Asphaltic matter (from montan wax process)	2.44*
Semi-anthracite (S.G.-1.40)	10	Petroleum residuum (San Joaquin)	< .01*	Asphaltic (?) residue (Lee Co., Va.)	2.95*
Semi-anthrac. ("Run of Mine")	16.5*	Petroleum residuum (So. Louisiana)	< .01*	Asphaltic (?) residue (Russell Co., Va.)	9.23*√
Low-vol. bituminous	3.86	Petroleum residuum (Tia Juana)	< .01*	Quisqueite	.67*
High-vol. bituminous	6.0	Petroleum residuum (West Texas)	< .01*		
High-vol. bituminous	6.9	Petroleum residuum (unknown loc.)	< .01*		
Cannel coal	12.38	Gilsonite ("L" grade)	0.2		
Graphite (from coal coke)	<7.0	Gilsonite ("VB" grade)	0.1		
Lignite	10.2–16.1	Graphite (from pet. coke)	<0.2		
		Impsonite	1.52*		

* Denotes analyses made by writer; other figures were supplied by sample donors.
√ Denotes sample analyzed was obviously impure.

530° C for anthraxolites whereas it occurs between 420° and 470° C for the anthracites.

"Glow Points."—The "glow points" were determined for many of the investigated high-carbon compounds. The temperatures for these were higher for all of the anthraxolites checked than for the anthracites. Whereas the values for the anthracites ranged between 595° and 610° C, the values for the anthraxolites ranged between 625° and 660° C. The Virginia anthraxolite gave values ranging between 635° and 655° C. None of the substances definitely derived from oil gave values higher than 530° C (the value given by the impsonite).

Microscopic Examination.—Thin sections of the Virginia anthraxolite are opaque. No structures suggestive of organisms were found by examination of etched surfaces of the anthraxolite. None of the other anthraxolites were available in specimens large enough for this type of study.

Spectrographic Analyses.—Spectrochemical investigations of many of the substances and of the ashes of some of them indicated no elements as being restricted to or even more characteristics of the substances related to oil versus those related to coal.

Ash Content.—Ash content was determined for those samples for which the figure was not supplied—that is, for those which were available in samples of size sufficient to permit accurate determinations. The values obtained are presented on Table 2. As is apparent, the ash content was found to be less than two percent by weight for all of the substances definitely derived from oil and greater than three percent by weight for all the investigated substances derived from coal. It should be noted with this regard that the ash content for the Montgomery County, Virginia is given as < 2.14 percent rather than merely as 2.14 percent because it was impossible to get "pure" samples by any of the separation methods used and it is believed that the impurities may have added to the ash content value.

DISCUSSION OF DATA

X-ray Data.—As noted in the previous section, the investigated materials may be placed into eight or possibly nine categories on the basis of their x-ray diffraction patterns. It is of special interest with regard to these that:

(1) Four of the categories include both substances known to have been related genetically with coal and substances known to have been related genetically with oil. These are the first category, which includes graphite produced from coal coke and that produced from petroleum coke; the second category, which includes all the coals except the cannel coal and also includes the oil-derived impsonite and asphaltic residua from Virginia (as well as most of the anthraxolites); the fourth category, which includes cannel coal and lignite as well as the rock asphalts; and the fifth category, which includes montan wax which is derived from lignite as well as the San Joaquin petroleum heavy vacuum residuum.

(2) Only two of the categories include materials of only one or the other derivation—category six includes only the asphaltic matter from waxes as

derived during the production of montan wax and category seven includes only crude residua. Possibly, however, category eight is also of this type. Included in it are the crude oils, the gilsonites, and the "anthraxolite" from Great Slave Lake, N. W. T., Canada. The last named substance has not been proved to have been derived from petroleum. It might be added with regard to this substance, however, that the quotes are the writer's and they were added, even before the substance was submitted to x-ray analysis, on the basis of the fact that the material occurs as globules within vugs and because it "powders" to a resin-like brown material.

(3) Remaining is the category which includes the quisqueite and Red Lake, Ontario anthraxolite (category IIa). The origin of neither of these has been associated with either oil or coal.

Obviously, x-ray studies will not serve to distinguish between oil- and coal-derived substances.

Numerous other interesting data which have been derived from this part of the investigation may be given:

The data appear to be at odds with Young's (23, p. 2018) statement that ". . . all of the coals are of the one-ring type, with variations in the spacing of the ring, diffuseness, and intensity." However, the discrepancy actually is a matter of interpretation of patterns. Young did not consider the low-angle intensity maximum to be significant—he believes it to represent only low-angle scattering—and he made no mention of the higher-angle intensity maximum(s). The writer believes that earlier work such as that of Hofmann and Wilm (11) and that of Franklin (7), along with that done as part of this investigation, establishes without doubt the fact that the intensity maximum at the low angle is not merely manifestation of low-angle scattering but manifestation of structure of the materials analyzed. As is shown (Fig. 1) blank slides gave different intensities in this region and, further, different materials (Figs. 2 and 3) gave different intensities in the area. Also, the same material gave essentially equal low-angle intensity maxima no matter how it was mounted. The presence of the higher-angle peak(s) also has been recognized previously (*e.g.*, Hofmann and Wilm, 11; Franklin, 7). Those mentioned here are quite obvious on the writer's patterns and, in his opinion, warrant no further discussion.

The pattern given by materials in category IIa, which appears to be a combination of the main graphite peak and the maxima given by the coals, impsonite, *etc.*, has significance in that the substances—seemingly homogeneous—appear to be made up of both graphitic carbon and "non-graphitic carbon." The patterns appear to corroborate Franklin's (8) contentions that spacing in the "non-graphitic carbons" is constant and different from the spacing in graphite and that substances showing the former spacing, *e.g.*, substances here replaced in category II, are not—as is often supposed—merely made up of minute crystallites of graphite. Perhaps, however, the presence of both within one material also could be construed to bear on the possibility that "non-graphitic carbon" is but a considerably distorted graphitic carbon lattice that may be ordered with time (15).

The high-ash semi-anthracite and the low-ash semi-anthracite coals, which, as shown on Table 1, have differences in ash content of 15 percent, gave essentially identical patterns. This appears to be of significance because it would appear to indicate that it is the carbon substance(s), rather than materials that constitute the ash, that is (are) responsible for the patterns.

Perhaps also of at least passing interest is the fact that the coals of category II (that is, all but the cannel coal) can be arranged in order of their ranks on the basis of the definition of and intensity of the peaks that they yield—the lower ranks give peaks with poorer definition and lower intensities than those of the higher ranks; see also Siever (19).

Differential Thermal Analyses.—It appears that differential thermal analyses cannot be used to distinguish between oil- versus coal-derived substances. For example, the impsonite (of oil kinship) gives essentially the same curve as that given by low volatile coals. Further, the anthraxolites, even the New York anthraxolite which quite assuredly was once fluid (therefore, oil or oil-like?), yield curves similar in all essentials to those given by anthracite coals.

Concerning the results obtained in this part of the investigation, the writer would like to suggest that the exothermic reaction, which appears to have escaped definite correlation with any certain phenomenon to the present, should receive more complete study. It might throw light on many problems such as plasticity and cokeability of coals.

"Glow Points."—Temperature for "glow points" of the different materials also appear to offer no way to distinguish between substances consanguineous with oil versus those related to coal. Although none of the investigated substances known to be oil derivatives gave a value higher than 530° C (the value given by impsonite), many coals also gave values below this temperature. Further, the New York anthraxolite, which appears to have been at one time in its history liquid (oil or at least oil-like?!), has its "glow point" = 630 ± 5° C which is higher than the value obtained for anthracite.

Microscopic Examination.—The lack of recognizable organic structures in high rank materials such as the Montgomery County, Virginia anthraxolite has no real significance in the writer's opinion. It certainly cannot be construed to preclude derivation from coaly or oily material.

Spectrochemical Analyses.—The fact that neither the oil-derived substances nor the coal-derived substances contain any elements that characterize only their group and do not occur in the other group appears to preclude utilization of the method for distinguishing substances of the one kinship from substances of the other.

Ash Content Analysis.—As noted above, the ash content was found to be less than two percent by weight for all of the substances definitely derived from oil and greater than three percent by weight for all of the investigated substances derived from coal. This is in line with previous studies which have resulted in statements to the effect that two to three percent is as low an ash content as can be expected for coal—although there are, of course, reports of special fractions from coal that run as low as .57 percent (10). It might be suggested on the basis of these data that ash content could be used to distinguish between coal- and oil-derived substances. Although this prob-

ably is basically correct, the writer would prefer to modify it to the following: If the ash content of a high-carbon solid is less than about two percent by weight, the substance probably, although not necessarily, was derived from oil; if, on the other hand, its ash content is more than about two or three percent by weight, the material could have been derived from either oil or coal. The latter dual possibility is added because it is believed quite possible that when oil migrates, especially if it concomitantly becomes increasingly viscous, it may pick up impurities that could add to its ash content—particularly if it migrates through something like a fault gouge. Further, as oil is converted to a solid high-carbon compound (probably mainly by loss of volatiles) there necessarily would be a relative increase in percent composition of insolubles (ash content).

CONCLUSIONS

Two main conclusions have been reached as a result of this investigation:

1) None of the investigated methods appear to offer a means of establishing unequivocally the genetic relationships of anthraxolite and similar high-rank solid high-carbon compounds, the field occurrences of which preclude definite determination of their origin.

2) Ash content may be at least suggestive as to the consanguinity between the solid high-carbon compound(s) in question and oil or coal, *i.e.*, if the ash content is less than about two percent by weight, the substance probably, although not necessarily, was derived from oil or an oil-like material, whereas if the ash content is more than about two or three percent by weight, the material could have been derived from either oil or coal. It should be emphasized, however, that this is in no way unequivocal.

It would appear that the presence of anthraxolite (ash content < 2.14 percent) at the Montgomery County, Virginia locality may indicate that oil is (or at least has been) present nearby.

Further, it would appear that the data presented here may suggest that contentions of workers like Schopf (18) and Berl (2) that there is no real division between oil and coal, that all suggested divisions are arbitrary, and that all these materials may be derived from essentially the same materials are correct. Certainly all high rank materials (the end products?) have quite similar properties.

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May 26, 1956

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A CRITICAL EVALUATION OF THE CLASSIFICATION OF ORE DEPOSITS OF MAGMATIC AFFILIATIONS[1]

A. D. MUTCH

ABSTRACT

The purpose of this paper is fourfold:

1) to summarize some of the relative data; 2) to point out some of the weaknesses of the present systems of classification; 3) to suggest the lines along which modifications should be carried out; and 4) to propose a system for categorizing the relative geological data.

It is concluded that there is a need for a more effective system of classification of ore deposits in general and those of magmatic affiliations in particular, based on all recognizable geological variations, and, as far as possible, free of any terminology or artificial divisions based on theoretical considerations.

INTRODUCTION

Economic geology is that branch of the science of geology particularly concerned with the more immediate application of geological knowledge in the service of man. Although the name would seem to imply it is an applied science, there is a very important theoretical side in which the direct evidence, along with indirect evidence and data from other sciences, is used to interpret geological phenomena. The division between the applied and theoretical is often obscure, for at times it is difficult to record geological data, or to apply the observed relationships, without introducing interpretations based on theoretical considerations.

In setting up of any method of classification of geological systems, it is essential to separate the factual from the theoretical. This is particularly true in regard to ore deposits which are for a large part formed by processes that cannot ever be expected to be observed. Thus, in this paper the suggested modifications of the present systems of classification will be of a type which will be based on observable criteria, rather than inferred processes suggested by geological evidence.

Background of Paper.—This paper was first visualized in 1948 while the writer was an undergraduate at the University of Toronto. Between 1948 and 1951 a fairly thorough grounding in the physico-chemical aspects of ore deposits was obtained from Prof. F. G. Smith of the University of Toronto while the writer was associated with Smith and others on research into the temperatures and pressures of mineral formation. Since 1951 experience in mining geology in the Sudbury area, along with a fairly extensive coverage of the current North American geological literature, has provided the remaining material necessary for the preparation of this paper.

[1] Presented before a joint session of the Society of Economic Geologists and the Geology Subdivision, A.I.M.E., New York Meeting, 1956.

Two recently published symposia have been of great assistance: The Fiftieth Anniversary Volume, Economic Geology (1) and The Crust of the Earth (2).

In order to exaluate a general paper of this type it is necessary to know the limitations of the writer's background and environment. Most of his experience has been in the Canadian Precambrian, largely in the Sudbury area. The lack of a complete library and the inability to study works not written in the English language are other limitations.

Scope and Purpose of Paper.—The scope of this paper is limited to ore deposits of magmatic affiliations, mainly because the writer is not qualified to make a more general coverage of the complete classification of ore deposits. Within the limits defined above, the purpose of this paper is fourfold: 1) to assemble in as concise a form as possible the significant geological and related physical chemical data; 2) to evaluate and criticize the systems of classification which have been suggested to date; 3) to suggest a basis on which modifications of the present systems of classification might be made; and 4) to propose a system of categorizing the relative geological data.

Present Classifications of Ore Deposits.—A brief summary of the historical development of the classification of ore deposits has been made recently by Alan M. Bateman (7) and will not be reviewed here.

In the past fifty years there has been a general acceptance of the division of ore deposits affiliated with igneous rocks, into the following broad subdivisions:

Magmatic
  early and late,
Pegmatites
  simple and complex,
Contact metasomatic,
Hydrothermal, and
Sublimates.

By and large the basis for the broad subdivisions is the type of phase from which the ore minerals were believed to have been deposited as indicated from direct and indirect evidence.

During the past forty years the classifications of W. Lindgren (21) in North America and those of P. Niggli (26) and H. S. Schneiderhöhn (32) in Europe have been widely accepted and applied. These have been recently reviewed by James A. Noble (28) who points out that these classifications are based on the magmatic theory of formation.

The strongly defended views of J. E. Spurr (36) stressing the magmatic nature of most metallic deposits have not been too generally accepted. W. H. Emmon's (14) detailed subdivision of the zonal relationships of ore deposits to igneous rocks was applied with some degree of success in areas of granite batholiths. The pre-World War II view point is summarized in two excellent compilations: Ore Deposits of the Western States (3) and Ore Deposits Related to Structural Futures (4).

Alan M. Bateman (6, 7) has contributed two of the more recent texts on ore deposits. His classification is along somewhat different lines than those

of Lindgren and Niggli, but in the detailed subdivisions he favors direct environmental characteristics rather than implied physico-chemical conditions.

There are some who maintain that metallic ore deposits even when intimately associated with igneous rocks are not one of the phases of magmatic differentiation. J. S. Brown (10) advanced the hypothesis: "that ores were vapourized from the horizons deep within the earth's crust, at which they had collected by various processes during the fusion of the incompassing rock materials"; a similar source as that postulated by Brown is suggested by J. R. Hillebrand (18) for ore deposits in the South Western United States.

There are many who only accept the magmatic theory of formation for a very limited number of ore deposits. Several of the great mining camps of the world, which are considered by some to be at least hydrothermal and probably of magmatic derivation, are considered by others to have been formed by sedimentary processes, e.g. the Rand gold and Rhodesian copper in Africa, and the White Pine copper and the Blind River uranium in North America. Many ore deposits in a metamorphic terrain are considered by some to be of magmatic origin but are believed by others to be the result of the differentiation of the elements during metamorphism.

In this paper the discussion is largely limited to cases that apply to the magmatic theory, but this is not to be taken as a blanket endorsement.

SIGNIFICANT GEOLOGICAL DATA AND PROCESSES

Although there is still a great deal to be learned, the science of geology is at a stage where the broad outlines and a considerable number of the details that will be required for complete understanding are known. Most of these relationships are summarized in the Crust of the Earth (2), and many of the more important phenomena of ore deposits are discussed in the Fiftieth Anniversary Volume of Economic Geology (1).

Major Features.—It is now generally accepted that the positions of the great ocean basins and the continents were determined early in the history of the earth. Globe-encircling structural belts of disturbance are recognized with the Circum-Pacific belt and the Alpin-Himalayan belt being active in this present geological age. In the ocean basins these structures are the axis of volcanic island belts; away from these areas of structural disturbances are great areas of relatively flat-lying sedimentation.

Many large areas of the crust of the earth are abnormally high in certain elements. This may be due to some unknown primordial feature or to the action of sedimentary, metamorphic, or igneous differentiation. The genetic association of ore deposits of specific metals with certain types of igneous rocks is well known and there is probably a similar relationship to those deposits common to sedimentary and metamorphic environments.

By definition epigenetic ore deposits are later than the rocks that enclose them. Generally a mineral belt is associated with a great regional structure or discontinuity but the ore bodies themselves are commonly found to be associated with structures that are limited in extent and intensity.

There is a wide range in the conditions in the environment in which ore deposits are formed. Some of these variables are: depth, temperature, pressure, and intimacy of association with the implied source.

Transport and Deposition.—There are many media of transport and methods of deposition available to transfer the various elements through the crust of the earth, which range from atomic migration through the intermolecular spaces and intergranular boundaries to the great intrusions of silicate melts, but to generalize, it can be stated that most elements are localized in structures by mineral deposition from: instrusive bodies, replacement, and crystallization from solution.

Variations in Space and Time.—Differentiation is a word that reoccurs many times in the discussion of geological processes. In effect it means variations in space and time. In sedimentary processes material is sorted by mechanical means and many of the mineral components are commonly determined by variations in the chemical environment; in metamorphism, the degree is generally determined by depth of burial and temperature; and in igneous processes the various phases form at characteristic temperatures and pressures, the final resting places of each of these components often far removed one from the other.

In ore deposits, phenomena of alteration haloes, zoning, and mineral paragenesis are all expressions of variation in space and time. Of these three only mineral paragenesis will be discussed in any detail.

The Paragenesis of Mineral Formation.—Much has been written on this subject particularly in regard to the mineral succession in veins. In rocks the succession is well recognized; in veins there are many summaries but these are often qualified with many exceptions and are not of too much use.

Reference to any simple phase diagram shows that with decreasing temperature the sequence of crystallization in any system tends to begin with the component which is most abundant or has the highest freezing point; for components in solution the same type of sequence occurs, the first crystals to form being the highest in the most abundant or most insoluble component. In igneous rocks, where the range in composition is not too great, the sequence of mineral formation is fairly well recognized and is adequately defined by N. L. Bowen's reaction series (8). In pegmatites the sequence is also well defined on a general basis: first to form are the large volume of simple minerals formed by the major components; and second the more complex minerals formed by the minor components; Turner and Verhoogen (37, p. 331) refer to Fersman's detailed classification of this late sequence in pegmatites. A more complete description has recently been given by R. H. Jahns (19).

Many summaries of the paragenesis of vein minerals are to be found in the literature, e.g. W. Lindgren (22), P. Niggli (26), W. H. Newhouse (25), Mark. C. Bandy (5), J. S. Brown (10). Lindgren has generalized this standard sequence on a mineralogical basis and Niggli on an elemental basis, but in practise these are difficult to use. Without reviewing the extensive literature the writer suggests that the following generalized sequence is typical for the mineral paragenesis in most epigenetic environments:

1) Silicates
2) Oxides MO
3) Sulphides
   a. MX_2
      Carbonates etc. (AXO)
   b. MX
   c. M_2X

and 4) Metals.

Newhouse pointed out that the sequence is generally in decreasing order of the heats of formation and on the whole follows the Schuermann series Fe, Co, Ni, Zn, Pb, Cu, Ag, Hg.

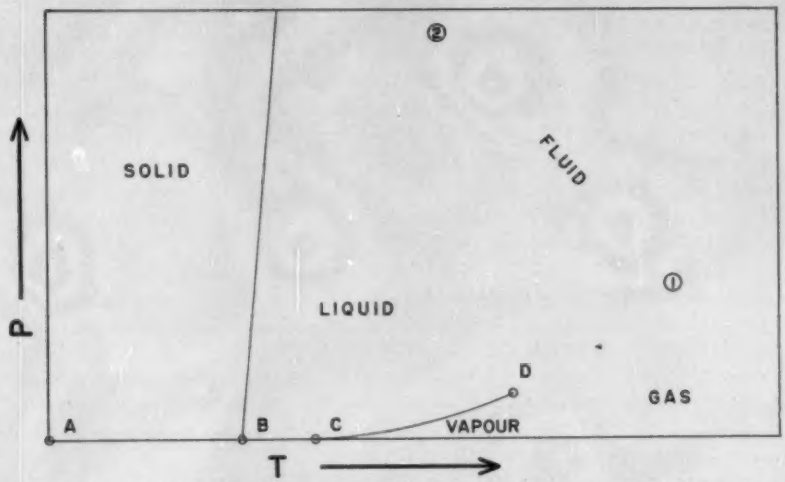

FIG. 1. Generalized diagram of the solid, liquid, and gas phase of an ideal substance in relation to temperature and pressure where: A—absolute zero, B—melting point, C—boiling point, D—critical point. See text for Note 1, by F. G. Smith (34), and Note 2, by Gutenburg (17).

Variations throughout Geological Time.—Everything in nature appears to have a life cycle. In the history of the earth, although there is little reason to believe that there has been any change in the fundamental laws or processes, there is abundant evidence that there have been systematic changes in the geological environment. Two pieces of evidence that support this statement are:

1) the great ranges of iron formation are Precambrian in age; whereas
2) the formation of large masses of limestone is limited to the post-Precambrian period.

In the light of these known variations it is logical to expect that there are parallel variations in the ore deposits formed at various ages, a condition that may be further emphasized when the effect of longer periods of erosion of the older formations is considered.

SIGNIFICANT PHYSICO–CHEMICAL RELATIONSHIPS

Terminology.—In the discussion of ore deposits from a theoretical point of view it is important that the physical type of the phase to which the ore is related to is defined. The possible types of physical phases are: solids, liquids, gases, vapors, and fluids. The term solutions is widely used in the literature, but since all geological systems are of mixed components and thus solutions the term is in effect all–inclusive and thus valueless.

Figure 1 is a generalized diagram of the relationship of the solid, liquid, gas, vapor, fluid phases of any typical substance. The terms solid, liquid, gas, and vapor are fairly well understood for single component systems at atmospheric pressures, but in the temperature and pressure ranges and multi-component systems such as exist in the geological environment, the sharp boundaries between the various physical phases disappear. The physico-chemical relationships of supercritical fluids have been recently reviewed by F. G. Smith (34). He uses the term fluid for the area of continuous transition of properties between the liquid and gas phases that exist above the critical temperature. G. C. Kennedy (20) demonstrated this continuous transition of the properties of density and solubility in the silica–water system. B. Gutenburg (17, p. 2) has pointed out the need of defining of the term fluid at a very high pressure on the solid-liquid boundary.

In a single component system the vapor phase is limited to that part of the gaseous phase which is below the critical temperature and pressure; but in a multi-component system a vapor phase will form once the sum of the partial pressures of the substances in solutions exceeds the confining pressure. It is by this process that a hydrothermal phase is formed at some stage in the crystallization of most rocks. The point at which this occurs has been defined by N. L. Bowen (8) as the second boiling point. Whether or not the 'vapor' is a vapor, liquid, fluid, or gas is dependent on its composition and the temperature and pressure of the environment.

The Various Physical Phases in Igneous Geology.—Based on geological and other evidence the existence of the following different types of phases in the crust of the earth is almost universally accepted:

Silicate liquids
A. Low water, igneous and volcanic rocks
B. High water, pegmatites
Oxides

Separate phases of the spinel group minerals possibly as liquids, more probably as crystal mushes.

Sulphides
Liquids

Hydrothermal
A. Water, liquid-fluid
B. Carbon dioxide, fluid-liquid

Gaseous
A. High water gaseous-vapor (in fumarole and volcanic vents)
B. Sulphur vapors (volcanic vents)

The above conclusions were generally accepted before the great body of relative experimental data of the last few decades was available. Since that time largely at such institutions as the Geophysical Laboratory, Carnegie Institution of Washington, the general features of the rock systems have been duplicated in simple but comparable systems.

Vapor Pressure Curves.—Figure 2 is a compilation of the vapor pressure curves of some of the substances of geological importance. Examination of these curves shows that the more tenuous components, those which would have the highest partial vapor pressures, are either acid or form acid radicals. In a magma these would be the components which would be expected first to enter the hyperfusible phase. Further, since they all have critical points at much lower temperatures and pressures than that of water, any solubility with

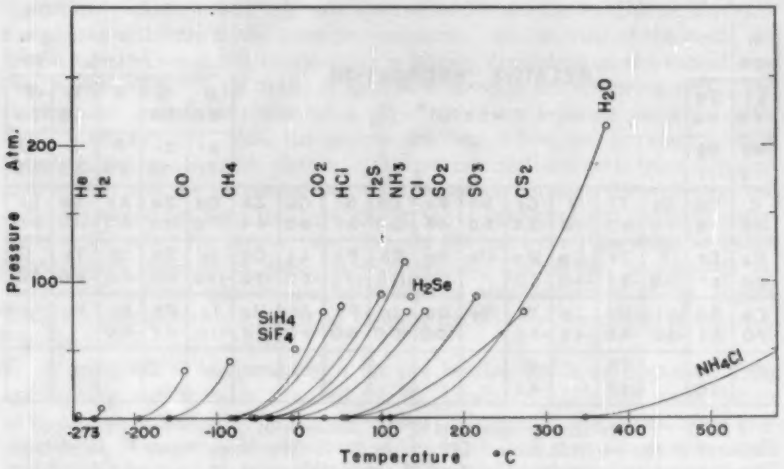

FIG. 2. Vapor pressure curves, boiling points, and critical points of various substances of geological importance.

water in the hydrothermal phase would lower the critical point of the hydrothermal fluid at this time. Salts in an aqueous solution such as NaCl are known to raise the critical temperature and there is every reason to believe that this relationship would also hold for metals in solution.

Although not shown on Figure 2 the critical densities of most of the substances are fairly high, commonly equal to that of water at 0° C. When this fact is considered along with the relatively low pressures of the critical points of less than two hundred atmospheres, it is apparent that under expected geological conditions high density hydrothermal fluids can exist relatively close to the surface of the earth.

Distribution of the Elements.—There is a very great range in the elemental distribution in the various types of geological environments. In the igneous

environment this distribution and the controlling processes are fairly well known. The major components that have a high melting point are largely in the form of silicates and oxides, and as pointed out by H. D. B. Wilson (39) and E. F. Osborne (29), the distribution of these elements is dominated by such features as atomic radii and coordination. The distribution of the minor elements is dependent on two essential types of control: 1) they substitute for the major elements which have similar atomic radii and coordination, and 2) they partition into the various available phases due to some dominating condition: the volatile components tend to enter the hydrothermal phase; the alkali components either remaining in the silicate phase or going into pegmatite phase; and the metallic-like elements tending to go into the sulphide phase.

The recognized data on the distribution of the elements has been arranged in several forms by different people. Among geochemists, Goldschmidt's

RELATIVE PROPORTION = 1×10^{-X}

H -2·9																
Li -4·4	Be -5·0											B -5·0	C -3·9	N	O --33	F -3·5
Na -1·5	Mg -1·7											Al -1·1	Si --56	P -2·9	S -3·3	Cl -3·3
K -1·6	Ca -1·4	Sc -7·0	Ti -2·2	V -3·8	Cr -3·4	Mn -3·0	Fe -1·3	Co -5·0	Ni -3·7	Cu -4·0	Zn -4·4	Ga -11·0	Ge -11·0	As -6·0	Se -8·0	Br -6·0
Rb -6·0	Sr -3·7	Y -3·8	Zr -3·5	Cb -4·5	Mo -6·0	Ma	Ru -11·0	Rh -11·0	Pd -11·0	Ag -8·0	Cd -7·0	In -11·0	Sn -6·0	Sb -7·0	Te -9·0	I -7·0
Cs -7·0	Ba -3·3	La-Lu -3·8	Hf -4·5	Ta -4·5	W -4·3	Re	Os -10·0	Ir -10·0	Pt -9·0	Au -9·0	Hg -7·0	Ti -11·0	Pb -4·7	Bi -8·0	Po	
	Ra -12·0		Th -4·7		U -4·1											

FIG. 3. The relative proportions of the elements in igneous rocks arranged in the form of the periodic table. Data after H. S. Washington and L. H. Adams, The chemical and petrological nature of the earth's crust, in Internal Constitution of the Earth: Dover Pub., Inc., New York, p. 81–106, 1951.

system is widely used but since part of this method of classification is based on the assumption of the possible existence of a sulphide phase deep in the crust of the earth, there has been a trend away from this system and a return to the direct use of the periodic table. Figure 3 is an example of the use of the periodic table as a means of recording the distribution of the elements in igneous rocks.

Elements in the same group in the periodic table tend to follow each other. The occurrence of all of the elements of group VII in the Sudbury District in recoverable amounts is an example of this relationship. In the ore at Opemiska Copper Mine, Quebec, as described by D. R. Derry and J. C. Folinsbee (13), copper, silver and gold occur in essentially the same relative proportions as recorded in Figure 3. The distribution of sulphur, selenium, and tellurium is an excellent example of the relationship of minor elements to a major ele-

ment in the same group. Where extreme differentiation has taken place, Te and Se are found at the lower end of the paragenetic sequence. Where no great differentiation is indicated, such as in massive sulphide bodies and sulphur deposits formed by sublimation, these elements occur as minor constituents. Still another example is the distribution of arsenic, antimony, and bismuth. These elements tend to occur early in the paragenetic sequence in the MX_2 type minerals in place of sulphur, or late in the sequence as metals or low sulphur compounds. A possible explanation for this double occurrence in the standard paragenesis is that in the early part of the sequence they were introduced as acid radicals whereas in the later fluids they travelled as metallic ions.

The Role of Temperature.—The crystallization of igneous rocks and the formation of the affiliated ore deposits are processes that take place in a falling temperature environment. In any system, under similar conditions, the various phases will form at the same temperatures. In the crust of the earth, the time it takes to reach this temperature is largely dependent on the rate of heat loss, which occurs in the form of heat flow through the enclosing rocks, and through the loss of heat that takes place when any separate phase migrates towards the surface. Near the surface, the rate of heat loss is rapid; deep in the earth, the rate is much slower. This increase in the time it takes a system to lose heat and the additional fact that at deeper horizons the hydrothermal solutions would not form until the higher vapor pressures and lower temperatures would allow for considerable time for the more complex space and time relationships common to deep–seated deposits. Conversely, it accounts for the short-lived and telescoped relationships of near surface deposits. Figure 4 is a diagrammatic representation of these expected temperature, vapor pressure, and time relationships.

A rapid fall of temperature in the ore bearing fluids as they ascend the ore bearing structures is assumed by W. Lindgren (21) and many others to be the major cause of the ore deposition. Epigenetic ore deposits are concentrations of minerals in structures of the earth. In many cases this would imply concentration of a large volume of heat in the ore–bearing structures. Thus the writer finds it difficult to visualize the maintenance of steep thermal gradients in the ore–bearing structures.

The Role of Pressure.—It has been developed previously by the writer (24) that the role of pressure in the formation of ore deposits has been underestimated. Pressure can be expected to be a major control for at least two stages in the formation of ore deposits affiliated with igneous rocks: 1) confining pressure is the environmental condition which has to be exceeded before Bowen's second boiling point is reached and a separate hydrothermal phase can develop; and 2) changes in pressures, such as occur as the various fluids found in the crust of the earth ascend towards the surface, can be expected to cause important reactions no matter whether these phases are silicates, oxides, sulphides, or hydrothermal.

In the crust of the earth the various igneous phases are all multicomponent systems composed of many different substances in varying amount. It has been demonstrated by R. W. Goranson (15) that in a silicate melt the pres-

ence of water lowers the freezing point many hundreds of degrees. The hyperfusible components form a separate phase once the sum of their partial vapor pressures exceeds the confining pressure. This can be expected to occur after the consolidation of the major amount of silicate material. Once a separate hydrothermal phase has formed this lighter material will be free to make its way toward the surface.

The pressure control on the amount of hyperfusibles in solution in a magma is in turn a major control on its freezing range. At depth, under high pressure, due to the presence of hyperfusibles, the freezing point of a magma would be much lower than that of the same magma in a near surface environment. This relationship can be expected to act in at least two ways:

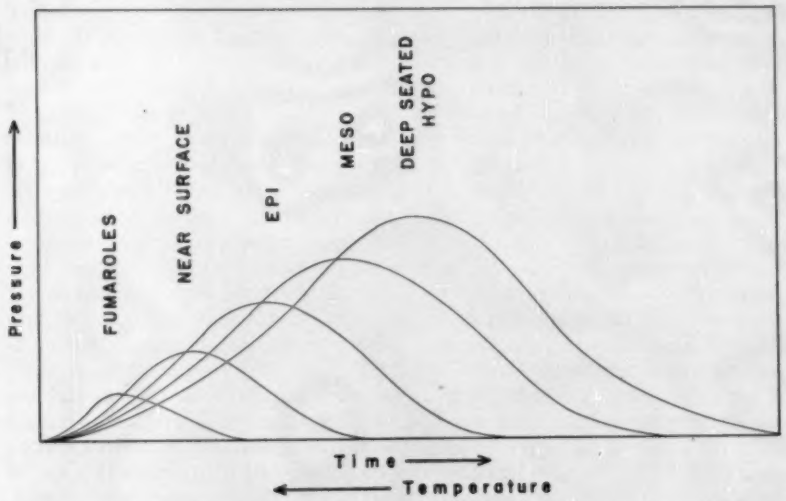

FIG. 4. Generalized diagram of the temperature-pressure-time relationship of like system at various depths in the crust of the earth. Modified after P. Niggli (26). See W. Lindgren (21, Fig. 11).

1) magma with little excess heat will freeze deep in the crust of the earth as soon as the separate hydrothermal phase begins to form, 2) phases that do not develop until a fairly low temperature is reached in an environment high in hyperfusible components could not form near the surface of the earth where the hydrothermal phase would separate off at a high temperature.

It is suggested by the writer the reason that pegmatites do not form near the surface may be due to the fact that the confining pressure is insufficient to hold in solution the hyperfusibles necessary to form the second high water silicate phase from which pegmatites are no doubt derived. The same conditions would be a satisfactory explanation for the lack of near surface sulphide phases. The vapor pressure curves examined above suggest that for

pressures of less than two hundred atmospheres this would apply. In discussing the classification of ore deposits Nobel (28) concludes that epithermal type ore deposits belong in a class by themselves. The writer suggests that the physico–chemical conditions as defined above may be the explanation of this fact.

Figure 5 is a compilation showing the approximate relationships of the freezing point curves of the various geological phases, one to another, at various temperatures and pressures. Two features are stressed: 1) the rapid lowering of the freezing point of granite with increasing pressure; and 2) the non-existence of independent sulphide and pegmatitic phases in a low pressure environment.

It was developed above that the loss of hyperfusibles through the second boiling point is a major cause of the rapid freezing of an intruding magma.

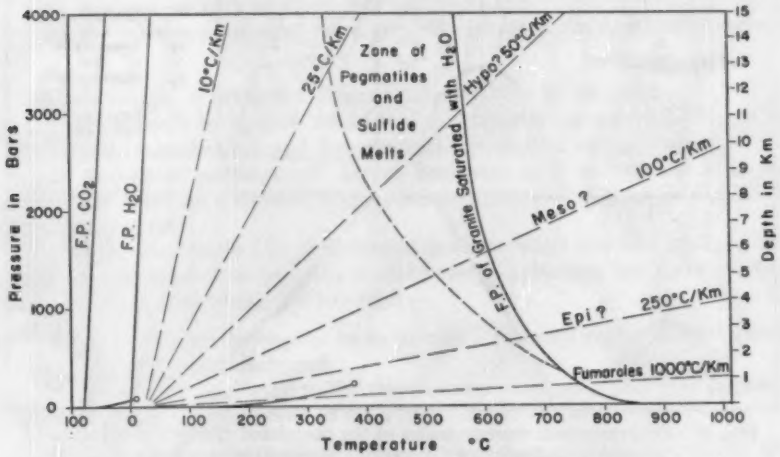

FIG. 5. A diagrammatic representation of the relationship of the fields of pegmatite and natural occurring sulphides to the freezing point curves of CO_2, H_2O, and granite and various geothermal gradients. Freezing point curve of granite as plotted by F. C. Smith in private report, January, 1951.

The same process can be used to account for major changes in hydrothermal fluids and in the case of sulphide or pegmatitic injections the loss of even a minor amount of hyperfusibles or sulphide vapor could be expected to cause crystallization at a catastrophic rate.

Figure 6 is a diagrammatic representation of the possible pressure changes in an ore–bearing structure. The driving pressure is considered to be petrostatic pressure. Up to, and above, the structural trap the loss of pressure is considered to be largely limited to the hydrostatic head of the ore fluids themselves. One implication of this interpretation is that the zone of ore deposition is related in space to both the source and the surface that existed at the

time of ore formation. It is the writer's opinion that the structures in which epigenetic deposits are formed should be considered as zones of fractional distillation where pressure releases rather than temperature drops are the dominating environmental control.

CRITICISM OF THE PRESENT CLASSIFICATIONS

In a natural science, such as geology, the setting up of a generalized classification of any observed phenomena is both the attainment of a milestone of achievement and the establishment of a new barrier against further unbridled rearrangement of the data. In many ways this is the situation that now ex-

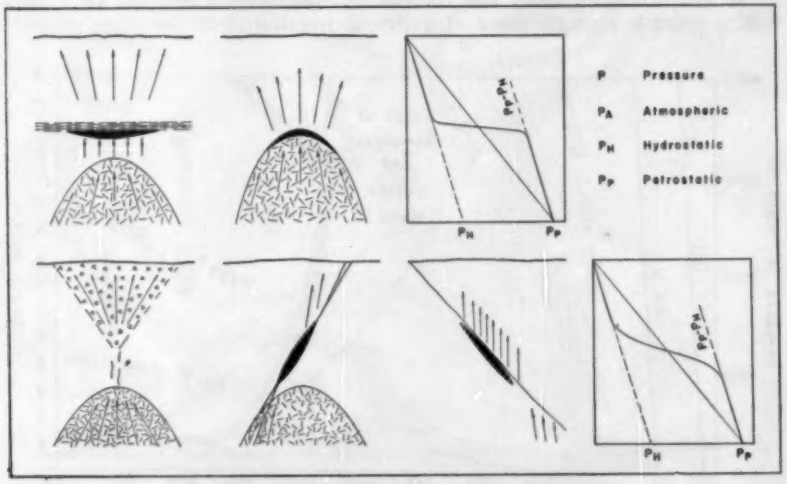

FIG. 6. Diagrammatic representation of the postulated changes in pressure in hydrothermal solutions in various ore-bearing structures.

ists in economic geology in regard to the classification of ore deposits and it is one of the purposes of this paper to demonstrate that this is so.

Above, most of the relative data have been summarized and in part analyzed; doubt has been cast on the role of temperature in the formation of ore deposits; the role of pressure, both as the determining control on the temperature of formation of the various phases and the deposition of the ore minerals, has been stressed; and the widely accepted conclusions that epithermal, mesothermal, and hypothermal orebodies were formed at progressively lower depths and higher temperatures has been discounted.

Among the orthodox school of W. Lindgren, P. Niggli, H. S. Schneiderhöhn, E. H. Emmons, L. C. Graton, A. M. Bateman and others, and even including J. E. Spurr, there is much common agreement on the various physico-chemical phases which exist in the crust of the earth.

In the light of recent data on the formation of vein quartz and the source of the silica as demonstrated by H. Schmitt (30) and R. C. Boyle (9), it has been fairly conclusively shown that Spurr over envisioned the role of vein dike injection of ore magma.

Probably the major weakness of Lindgren's (21, p. 212) classification including the further detailed subdivision by Graton (16) is the more or less general acceptance of the temperature and pressure conditions as ascribed to hydrothermal ore deposits formed at various elevations. J. E. Spurr (36, p. 19) was of the opinion that near surface ore deposits not only had the whole range of temperatures of formation and were in some cases hotter than deep seated equivalents, but suggested that the temperature of formation of a deposit was dependent on the economic mineral that was present. Probably the major control on the temperature of formation of an ore deposit is twofold and dependent on:

1) the igneous rock to which it is affiliated; and
2) the relative position of the economic mineral in the standard paragenesis.

This relationship is presented diagrammatically later in the paper.

There appears to be little doubt that the deposits classed by Lindgren as epithermal, mesothermal and hypothermal are indeed representative of deposits formed at progressively deeper horizons; it is unfortunate that the names are based on a theoretical consideration rather than some less infallible descriptive term.

Alan M. Bateman's (6) classification is more recent and less involved and at first sight appears to be fairly invulnerable to criticism, but there are two aspects which tend to make it too rigid:

1) there is some ambiguity as to in which category replacement deposits should be classified; and
2) it does not lend itself to the classification of deposits that may be intermediate or transitional to the various major divisions.

Bateman divides hydrothermal deposits into two subdivisions: cavity filling and replacement. He also considers replacement to be one of the processes involved in the formation of pyrometasomatic deposits. Further he concludes (7, p. 131) that water plays the dominant role in replacement. But sulphide replacement is well known in the anhydrous environment of a blast furnace. Since this is so, perhaps magmatic deposits should have a subdivision to include this process; perhaps pyrometasomatic deposits would be better named if they were called magmatic replacement deposits.

The division between magmatic injections and hydrothermally formed deposits is not universally accepted. More and more evidence is accumulating to suggest that hydrothermal alteration alone is not conclusive evidence as to the type of phase from which the sulphide minerals of all ore deposits are deposited. In the realm of regional petrological provinces great igneous intrusions of periodite and splites are preceded or associated with the introduction of considerable hydrothermal and carbonaceous fluids perhaps from the

abyssal depths, and it may be these hyperfusal components are the fluxes which are necessary for the formation of most igneous rocks. In the Tintic District T. S. Lovering et al. (23) found that hydrothermal alteration preceded the intrusions of the monzonite porphyries and the ore. In the Sudbury District large volumes of tuffaceous rock high in carbonaceous material preceded the formation of the norite-micropegmatite irruptive and at some of the mines it is indicated that very large volumes of hydrothermal fluids preceded the sulphide mineralization. Stanley Davidson (12) in describing the Falconbridge Mine where there is extensive pre-ore hydrothermal alteration concluded that the ore fluids were of a denser media than that commonly ascribed as hydrothermal. A similar observation has been recently made by V. Vahatala (38) in regard to the mineralization at Outokumpu, Finland.

In discussing the presence of sulphide minerals in a magma S. J. Shand (31) concludes that there is no apparent reason why they should be present and used the following formula as a demonstration:

$$RO + H_2S \rightleftarrows RS + H_2O$$

With the large excess of H_2O which Shand is ready to accept is the condition which exists in a magma, the reaction will move to the right. Shand's argument would appear to hold for a closed system, but the formation of ore deposits does not take place in such an environment. If we consider the same equation as an open system and allow water to escape, once its vapor pressure exceeds the confining pressure, as it apparently does in nature, the equation will move to the left and a separate sulphide phase will form at the same time as the hydrothermal phase is discharging; this sulphide phase having a lower vapor pressure and higher specific gravity would tend to remain in the magma chamber until much later in the sequence. There are many ore deposits where such an interpretation would fit the events. No special chemical composition is required to keep the metals in solution for it is in fact an example of Spurr's ore magma.

There may be a continuous transition between magmatic sulphide deposits and deposits in which there is little doubt that all the minerals were transported and deposited by hydrothermal solutions. It is possible that there may be another continuous series between Niggli's pneumatolytic veins and pegmatites and hydrothermal veins. F. G. Smith (33) has defined this problem and completed a very comprehensive coverage of the literature (35) and is conducting research aimed at resolving the many data. As long as there is real evidence of the possible existence of a continuous series between various types of deposits the present practice of attempting to make all mineral deposits fit into rigid classification will tend to retard rather than advance the final goal of a systematic classification of epigenetic ore deposits.

The metallurgical interpretation of the formation of ore deposits as proposed by J. S. Brown (10) has not been generally accepted. The writer finds two major weaknesses in the argument: 1) the postulated primordial sulphide phase deep in the crust of the earth; and 2) the vapor transfer of the metallic elements from the abyssal depths to the area of ore deposits.

Brown's sulphide layer cannot be disproved. The writer is willing to accept that fluids largely composed of water, CO and CO_2 from the abyssal depths may be the fluxes that key off formation of igneous rocks, but the vapor pressures inherent in these substances are many thousands of times greater than those proposed by Brown, and at depth the co-existence of these vapors would be in effect a very dilute metal-bearing hydrothermal solution. Even conceeding the existence of the primordial sulphide layer as proposed by Brown the confining pressure of only a few feet of rock would be great enough to prevent the formation of a separate vapor phase. Although the writer does not accept Brown's interpretation the method of classification suggested herein is not dependent on this opinion and is compatible with any other mode of formation, including: metamorphism, laterial secretion, and even sedimentation.

SUGGESTED BASIS FOR MODIFICATION OF PRESENT CLASSIFICATIONS

Any system of classification of ore deposits is used as both a tool and a guide: the applied geologist uses it as an aid in the search for new deposits; his academic brother for new understanding and knowledge. In order to be most effective and fulfill this twofold purpose the system of classification should be based on observable relationships with the theoretical or implied relationships relegated to a complementary position. The general principles to be observed could be stated as follows:

1) only observable relationships are used to categorize the data;
2) it is in the form of an effective tool to aid in the search for new deposits;
3) the system is adaptable to major changes in interpretation and as far as possible the terminology is independent of the theoretical or implied conditions.

When such a system is used the various empirical relationships will be systematically arranged in a form that would be available for a more complete understanding of the distribution and the mode formation of ore deposits.

Most of the features that have to be evaluated in order to make a complete classification of ore deposits on an empirical basis have been listed by P. Niggli (27). These, along with some others, are included in the following list of the major features which should be considered.

1) the major economic elements,
2) the ore minerals and their position in the standard paragenesis,
3) the character of the mineralization,
4) the dimensions of the ore bodies including weight, tenor, and vertical extent,
5) the environment of the ore deposit, both regional and local,
6) the relative position of the ore deposit; to the surface, and to the indicated source or affiliation,
7) geological age, and
8) the possible processes whereby the deposit was formed.

1) The Major Economic Element.—In practice most ore deposits are referred to by the element for which they are considered economic regardless of the indicated process whereby they were formed. The same precedent is usually given to the gangue minerals.

2) The Ore Minerals.—The type of ore minerals is an important feature of any ore deposit. It is suggested that the recording of the relative position of these minerals in the standard paragenesis would give a general classification useful for the comparison with other deposits.

3) The Character.—This should include an estimate of the mode of emplacement of the ore, such as: injection, replacement, fracture filling or any other process; the type of structures in which the ore bodies occur; and any other feature, such as the nature and the extent of the alteration and mineral zoning.

4) The Dimensions.—The tonnage and grade of any mineral deposit is one of the dominating factors of any mineral occurrence. Since there tends to be a variation in the tenor of ore minerals, e.g.: Cr, and Ni, or mineralization, e.g.: Au and Ag, it is important that this be recorded. Disregarding any changes in dimensions due to removal by erosion it is of utmost importance to evaluate the persistence to depth and the vertical extent of the ore bodies.

5) The Environment.—An attempt should be made to record the position of the ore deposit both in space and in time on a local and regional basis and, if possible, relate it to equivalent areas or processes elsewhere. This evaluation would include all observable features such as: structure, rock types, and relative time of ore deposition.

6) The Relative Position.—Any evidence bearing on: the depth of the ore at the time of formation; the relationship of the vertical extent of the ore to the present surface and to the surface that existed at time of formation; and the distance from the implied sources, probably should be recorded under the separate heading of relative position.

7) Geological Age.—Since there is good reason to expect that there may be a systematic variation in the character of ore deposits throughout geological time, the age of any deposit should be recorded.

8) The Process of Formation.—The relegation of the defining of the process of formation of an ore deposit to the end position should have at least two beneficial offsets:

1) alternative processes could be considered without changing the classification,
2) ore deposits could be grouped empirically without restriction by barriers of terminology and other perhaps artificial divisions.

POSSIBLE METHODS OF CLASSIFICATION

Since so little is known about the processes whereby epigenetic ore deposits are formed, perhaps it would be better to classify ore deposits on an empirical basis. Two such methods are suggested.

In Figure 7 the economic elements and their relative position in the standard paragenesis are related to the rock types with which these elements are

commonly associated. The intimacy of this association is believed by the writer to be a direct function of the relative position of the ore mineral in the standard paragenesis. The relative temperature of formation is indicated after the manner already suggested by A. F. Buddington, Joseph Fahey, and Angelina Vlisidis (11) in regard to spinel deposits affiliated with various igneous and metamorphic rocks.

A second and more speculative method is suggested in Figure 8 where the metals are arranged in relation to the various types of physical phases from which they were deposited, the depth of formation, and the position of the ore mineral in the standard paragenesis.

STANDARD PARAGENESIS

ROCK TYPES (Temperature ↑)	Oxides	MO		AXO			
	Sulfides		MS_2		MS	M_2S	
	Elements						M
	Peridotite (Anorthosite)	Cr Ti Fe			Ni Cu Fe		Pt
	Gabbro	Fe Ti	Ni Co Pt Fe		Ni Cu Co (Pt) Fe		Ag Bi
	Diorite	Fe (Ti)	Fe		Cu Co Zn Fe		Cu
	Quartz Diorite	Fe	Fe		Zn Cu Pb		Au Ag
	Granodiorite	Fe Sn	Mo Fe	W	Zn Pb Cu (Sb)	Cu Ag	Au Ag
	Granite	Fe Sn	Mo	W	Zn Pb Sn Hg As	Sb As	Au Ag

← Temperature

Intimacy decreasing →

FIG. 7. Generalized diagram of the relationship of rock types—metals—standard paragenesis—temperature—intimacy of association for ore deposits of igneous affiliations.

PROPOSED METHOD OF CATEGORIZATION

To be effective any method of categorizing data should be designed to satisfy two conditions:

1) it should be able to tabulate all the required variables and degrees of variation, and
2) it should be adaptable to diagrammatic presentation.

The geological data of an ore deposit can be very effectively assembled under twenty or more major and minor headings and the variations within these divisions can be arranged in some sort of decimal system.

Data in this form can be assembled on the punch card system where once

recorded it can be sorted mechanically as desired. A simplified form of plotting such information could be on a standard circular form, where it is an easy matter to compare the various features of one ore deposit with another.

Figure 9 is an example of comparative diagrams for epithermal, mesothermal, and hypothermal gold deposits where the following variables are plotted:

chemical and mineralogical—all native gold, gangue quartz;
petrological—all related to albite granite;
dimensions—increasing vertical extent and tonnage from epithermal to hypothermal;
—decreasing tenor from epithermal to hypothermal;
structure—epithermal associated with gravity faults, hypothermal with thrust faults;
—epithermal in open fissures, hypothermal in tight fissures.

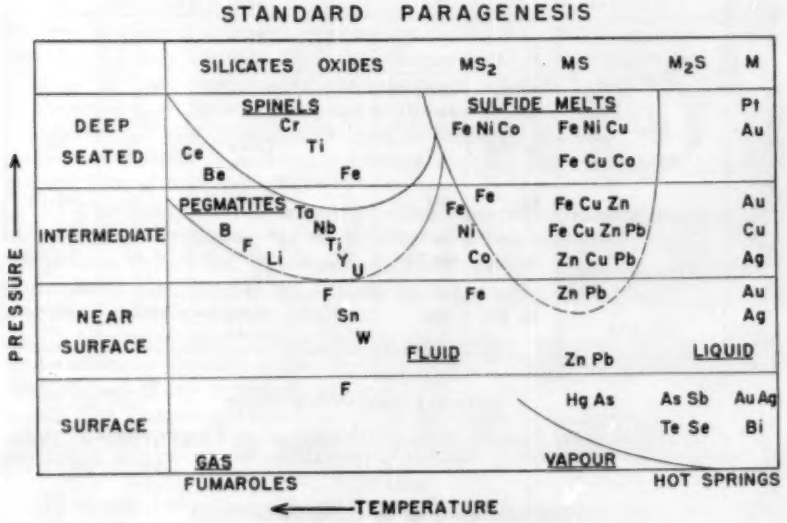

FIG. 8. Generalized diagram of the possible relationships between some of the various types of physical phases in igneous geology to the standard paragenesis, temperature of formation, and ore elements.

Of course, seldom will it be possible to tabulate all the desired information about a particular deposit; nevertheless, the use of a standard form or check list will be an inducement to record all available data.

Since the purpose of this paper is only to criticize and to suggest the basis on which the present classification of ore deposits should be modified no further examples will be given at this time. It is hoped others will find some merit in the above suggestions and make modifications, additions and improve-

ments to the method. Although there is still much to be learned about many of the detailed processes involved in the formation of ore deposits, it is the writer's opinion that the applied geologist, perhaps even more so than his academic associate, should conduct a continuous frontal attack on at least the categorization, if not the final classification, of all mineral deposits, and that if this is to be done most effectively he must be continually on guard against

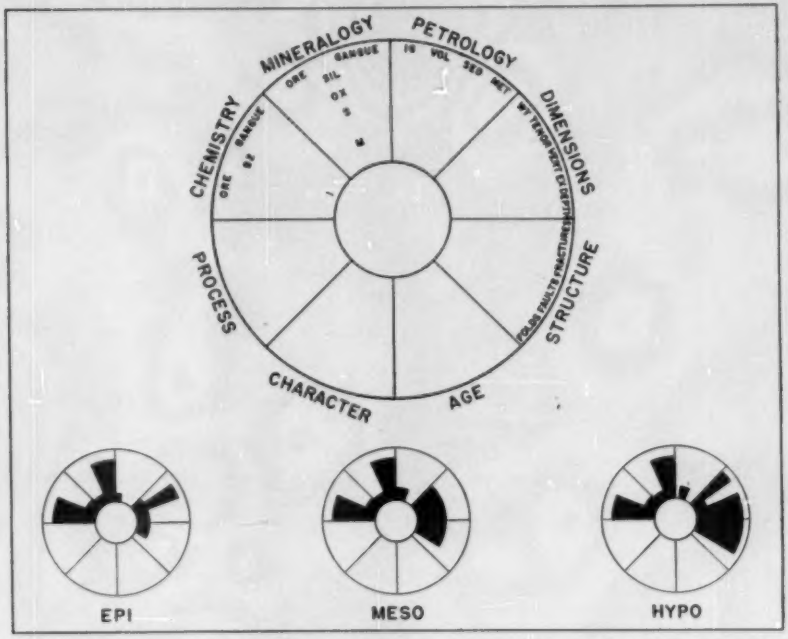

FIG. 9. A proposed graphical method for the recording of the various features of ore deposits, with an example of how it would appear when applied to quartz-gold deposits. (See text.)

the introduction of any terminology or artificial divisions which are based on, all or in part, theoretical considerations and interpretations.

CONCLUSIONS

In the light of our present knowledge of the process involved in the formation of epigenetic ore deposits the widely used practice of classifying these deposits by a genetic method appears to be premature.

A system of classification based on intrinsic properties, particularly if it included regional environmental features, although more involved, would be in the form of an effective tool for the search for new ore deposits and be a

great aid in the eventual development of a suitable genetic method of classification.

There is a need for the setting-up of a standard form for the recording of the various dimensions of any ore deposit and the use of the same to compile the descriptive information of all mineral occurrences. This would provide organized data which would be of great use in the fuller understanding of the distribution and the mode of formation of ore deposits, and would point to the areas where further field study and fundamental research would be most effective.

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I accept full responsibility for any statements or theories developed in this paper and gratefully acknowledge the assistance listed above.

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MINERAL RESERVES AND MINERAL RESOURCES

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On Behalf of and Approved by
A Committee of the Society of Economic Geologists [1]

ABSTRACT

This report is designed to clarify the meaning of the terms *reserves* and *resources* and to recommend, for common acceptance, rules and definitions to be observed in estimating reserves and resources.

All estimates for mineral reserves and resources rest on geologic appraisal, which contains many indeterminate elements. If the miner thinks the indefiniteness is too great, he reduces it by new exploration or development, but always there remains a residuum of uncertainty. For appraisals of whole countries or industries, fields of inquiry that require economic assessment, the geologic indeterminates remain large and dominant. Moreover, whereas the miner thinks in terms of the economic present or of the economic near future, the economist dealing with resource appraisal thinks of the more distant future and therefore takes into consideration deposits well beyond the miner's present interest. In doing so he must set arbitrary economic limits more far reaching than the geologic uncertainties. Thus, the miner and economist view the matter of reserves and resources within different frames of reference having different boundaries. The terms created by the miner to describe the ore reserves of his mine cannot appropriately be transported into the larger and more indefinite field of inquiry of the economist.

We recommend the following equation as defining the difference between "reserves" and "resources," the term "reserves" being limited to mineral material considered exploitable at present, and "potential ores" consisting of those deposits demanding more favorable conditions:

$$\text{Resources} = \text{reserves} + \text{potential ores}$$

But the conditions needed for the exploitation of "potential ores" vary from conditions only slightly different than at present to those that are widely different, so that a more complete equation would be as follows:

$$\text{Resources} = \text{reserves} + \text{marginal resources} + \text{submarginal resources} + \text{latent resources}$$

The appraiser can be guided by either equation, depending on the information available to him and on the purpose of his appraisal.

The above is a classification of resources. The reserve category itself has to be broken down. For the mine operator we recommend continuation of the traditional breakdown into "proved," "probable" and "possible," but according to the definitions given by C. K. Leith. For the person who would assess the reserve or resource position of an industry or of a region or of a nation, we recommend common acceptance of the classification

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(proposed and adopted by the U. S. Bureau of Mines and the U. S. Geological Survey) of "measured," "indicated," and "inferred" reserves, modified by combining "measured" and "indicated" into a category of "demonstrated" reserves.

A word of caution is necessary. Estimates of reserves and resources require constant scrutiny and periodic review. Moreover, such estimates are only a partial answer to those who use them, for they state only the quantity of material that a mine or a region or a country may contain. The user of the information would like to know, in addition, the rate of production the mine or region or country could support under variable economic conditions over some extended period into the future. Such information we as geologists and engineers cannot, of course, furnish.

WHAT exactly is meant by the question: "What are the iron ore reserves of such and such a country?" And along with this, "What rules must be observed in estimating these reserves?" Such questions have been the subject of numerous discussions.[2] The answer to the first has depended in the past on who asked the question and on who furnished the answer; the answer to the second has depended on who made the estimate. Yet clearly it is desirable that there be a single answer to each. We suggest such answers in this report. They are not completely new. In one way or another they have been proposed in the past; we simply rephrase them here in a context designed to be acceptable to all.

SUPPLEMENTARY POINTS OF VIEW

The crux of the confusion lies in the fact that the basic notions, and the terms used, do not have the same meaning for everyone, and that these variations in sense arise largely from the circumstances of their usage.[3] In general, two spheres of usage can be distinguished, first, that of the miner and, second, that of the economist.

Before engaging the considerable sums required to open a mine, the miner first estimates the tonnage of ore or quantity of metal that can be taken out profitably. He may or may not estimate the total amount—commonly he is satisfied with determining only that enough is present to justify the proposed investment. This estimate he calls the "estimate of reserves" of the deposit, and he keeps it up to date throughout the life of the operations—as costs and prices fluctuate, as known ore is mined out and new ore found, and as mining and processing technology improve—in order that he may know constantly, as fully as is practicable, how much ore he can continue to count on.

The point of view of the economist comes into play when the mineral potential of a region or of a country, as contrasted with that of a single mine or group of mines, becomes the item of interest. Everyone knows more or less clearly the importance of minerals in modern economy. The layman knows also, at least vaguely, that individual deposits do not produce indefinitely. Broadly speaking, different minerals come from different deposits differently distributed geographically, and the location of the sources of any

[2] See bibliography.
[3] See particularly Lasky, 1945.

particular material varies with time—slowly, perhaps, but steadily. Inversely to agriculture, which reproduces almost in the same spot, mining consumes little by little the riches that Nature offers to it, and is obliged to turn without cease to new deposits, or to new parts of old deposits. Because of this fact and because there is no end to civilization's demand for a continuing supply of mineral products, efforts are continuously made to visualize the future mineral capabilities of whole countries or regions. Manufacturers, financiers, statesmen and their economic advisors are all concerned with this problem, and the conclusions they reach and the decisions they must make are sound only in proportion as they are reliably informed.

The two approaches—that of the miner and that of the economist—are conceptually different, but they are not necessarily in conflict. In reality they are supplemental. The first has limited application, and the second depends on the first. Each is based on its own set of considerations.

THE GEOLOGIC SIDE OF APPRAISAL

Estimating the amount of ore that may be present in the ground involves so many factors that it is a difficult matter at best. Yet because of the nature of the subject the estimates must generally be made in quantitative form, and the very fact of utilizing numbers gives a false impression of precision.

The quantity of ore that will be extracted from the ground is not a definite figure, an objective reality that two equally competent persons will appreciate equally. Of course, once a deposit is exhausted, we usually know what it has given, but an attempt to forecast this figure beforehand must involve many assumptions: First, about the geologic type, quality, and total size of the deposit, and second, about future technology and economics. Accordingly, estimates of the quantity of ore that eventually may be extracted from the ground, as made by different observers, are rarely comparable. One estimate may be ten or even a hundred times another, yet both may be valid, each in its own context.

Before total exploitation, only an uncertain approximation can be made of the tonnage that can be extracted from a deposit—approximate, in the sense that the estimate always involves a margin of error; uncertain, in the sense that even the margin of error is not clear, as will be explained later.

Estimates of mineral potentialities—whether dealing with a single deposit or with a region in general—rest initially on geologic observation of the surface, supported, of course, by whatever mining works or drill-hole data may be present. This appraisal is based both on general geologic knowledge of the region and on a comparison of the particular deposit or area under study with other deposits or areas with which the geologist is in some way familiar. In particular and whether done consciously or unconsciously, he always classifies the deposit as to geologic type as a necessary first step in appraisal.

These intellectual operations—for we must frankly admit that that is what they are, however skillfully they may be performed—give rise to the rough estimates and to the uncertainties about which we have already spoken. The

margin of error and the uncertainties are too great for the miner; he therefore executes a series of mining works (trenches, bore-holes, pits, adits) designed to eliminate them. He does not care whether the geologist's assumptions and hypotheses are correct or false; he simply wishes more positive information. But such works tend to be costly, and so he undertakes them only if the geologic estimate has been favorable, and he continues to carry them out only to the point of being assured that he will have enough ore to support operations for some reasonable period; he knows that his investment can be worthless if its recapture is deferred too far into the future.

As to studies bearing on a whole region, these must remain satisfied with the geologic estimate only, as mining works extending over a whole region would be prohibitively costly. Herein appears the first divergence in the way the problem is approached by the miner and by the economist. The miner, interested in single deposit, can reduce the uncertainties of an estimate by further work, or not, as he desires; the economist engaged in long-term assessment of a region or country must accept them.

THE ECONOMIC UNCERTAINTIES

A mineral deposit is rarely a homogeneous mass having neat outlines. Its limits are most of the time undecided, and within it the grade is variable. The entire deposit is not economically exploitable, so that in order to estimate the tonnage that *is* exploitable, the estimator is obliged to choose more or less arbitrary boundaries and to make a number of arbitrary economic assumptions.

For the miner these economic assumptions are relatively precise, for he makes his estimate with major reference to the economic and technical possibilities then prevailing, using cost limits consistent with normal risk-taking and commercial production. The person making a long-term economic appraisal does not do this. He does not reason in the immediate present or even for five or ten years. Moreover, he does not deal with individual deposits, but with countries or industries. He is obliged to think of longer terms and so must take account of deposits that the miner would consider unexploitable. In fact, he takes into account deposits whose possible utilization is so far in the future that the miner often considers him quite impractical.

Moreover, from the time the appraiser ceases to base himself on current economic conditions he no longer has a fixed frontier of reference. Should he consider cost-price relationships superior to the present or inferior, and if so, by how much? Conceptually he is under no compulsion to impose any cost-price limits except as he desires. This factor involves arbitrary decision much more influential than the geologic uncertainties.

The miner and the economist clearly have a different appreciation of this subject. The economic factor exists for the miner, it is true, but it is relatively simple; moreover, for him it can be discussed objectively, with a reasonable chance of agreement. The arbitrary assumptions as to the market situation in a far-away future made by the economist, on the contrary, are rarely likely to be discussed with any measure of agreement.

BORROWED TERMINOLOGY

The first estimates of mineral productivity were made by miners—geologists or engineers; the economist's requirements appeared only recently. Consequently, for the earliest estimates the geologic uncertainties were felt particularly, because the miner had to try to reduce them by costly work, and it was natural that they should have influenced the terminology.

Thus were introduced into practice the terms almost universally used—*proved, probable* or *possible* reserves, or analogous terms. "Possible" reserves are a geologic estimate. If exploration or development verifies the geologic hypotheses or exposes the ore more completely even though not verifying the geologic reasoning, the "possible" reserves are transformed into "probable" reserves; finally, in order to define the conditions for exploitation, the miner executes still more mining work that practically eliminates the uncertainty and transforms the "probable" reserves into "proved" reserves.

The economist, on the contrary and as already indicated, must content himself, save in exceptional cases, largely with a geologic estimate, for he is dealing mainly with resources that are to be exploited in a future that extends beyond the life of the "proved" or even "probable" reserves. In addition, the economic assumptions he introduces make his estimates more tenuous than are even the miner's estimates of "possible" reserves. In making these estimates, however, the terminology created for the appraisal of the mineral *reserves* of a deposit has been converted into a terminology for the mineral *resources* of whole regions and countries.

The significance of this situation is brought out by the quantitative relationships. In the miner's usage, "possible reserves" usually range from about half as much as "proved" and "probable" combined to two or three times as much. But in the economist's usage, the term "possible" is applied to material that may add up to a figure more than a hundred times as large as "proved" and "probable" reserves combined (1, p. 171).

There is still another aspect that both miner and economist, as users of estimates of mineral potentialities, usually fail to appreciate—namely, the margin of error inherent in regional estimates. Such estimates, as explained later, are now commonly expressed in terms of *measured, indicated,* and *inferred* ore. Measured ore, the most certain of these categories, has by definition a margin of error of as much as 20 percent. In practice, this allowable maximum tends to become the rule. The margin of error for indicated ore is, of course, even higher, and for inferred ore higher still. Thus, for estimates that include all three categories, the margin of error is commonly on the order of 50 percent, and may be plus or minus. In the estimates used by the economist—wherein the amount of ore envisioned as being eventually used is so many times the amount in the proved and probable categories, or in the measured and indicated categories—the margin of error is even greater. Nevertheless, this does not nullify the utility of the estimates—it means merely that the user must be conscious of their frontiers and of the terms he employs in describing them.

THE CONDITIONING VARIABLES

From the foregoing, we see that the estimate of the mineral productivity of a deposit or of a region depends on at least two factors:

(1) The limit accepted for the economic possibilities of exploitation. For a single mine, this is usually expressed as a minimum minable, or cut-off, grade; for a region, in which each mine may have its own cut-off grade, the limitation has to be expressed in more general terms.

(2) The degree of certainty desired for the estimate itself—that is, whether the estimator wishes to include only "proved" reserves (as is done for petroleum, for example), or would include also the progressively less certain categories of "probable" and "possible" reserves.

Obviously, for the same deposit or the same region, at a definite period, the estimate increases (a) when a higher price or lower cost is obtainable, or (b) when a lower degree of certainty is accepted. It increases also as technology of recovery is improved, but this factor can be considered as encompassed by the cost-price relationship.

Thus, there is no such absolute entity as "the" reserves or resources of a mine or an area; there are only estimates applicable within particular economic limitations and degrees of certainty. For the sake of clear understanding between the estimator and the user of the estimate, these conditioning factors should in each case be specified.

A CLASSIFICATION OF RESOURCES—SOME NECESSARY DISTINCTIONS

Notice that in the estimate of reserves the miner generally assumes economic conditions roughly equivalent to present conditions. He considers that if more stringent conditions arise they will ultimately resolve themselves, and that he has the right to begin exploitation on the assumption that the present cost-price relationship will apply, on average, for the life of the reserves he then estimates. The economist, on the contrary, assumes that the economic circumstances of his more distant future will *not* be the same as the present.

Keeping this essential difference in mind, and in order to foster clear understanding, we suggest (following the distinction put forward by Lasky in 1949) using the term *reserves* for mineral material considered as being exploitable under existing conditions, including cost, price, technology, and special local circumstances. The term "reserves" would thus be used only in the sense that the miner understands it.

Reserves are thus only part of the total resources. The rest consists of that mineral material which, to be exploited, demands conditions more favorable than those currently existing, as well as further exploration to bring into consideration undiscovered deposits not currently included under the terms "possible" or "inferred." For this remainder we suggest the term "potential ores," although recognizing that realism will usually impose a limit in the evaluation of such material; it would ordinarily serve no purpose, of course, to include those mineral masses whose exploitation, for any reason—

nature of ore, tenor, geographical location—is difficult to visualize even in a faraway future—for example, rock in the United States containing only 15 percent of iron.

Accordingly, we have the equation:

$$\text{Resources} = \text{reserves} + \text{potential ores} \tag{1}$$

It is useful, and for some countries and some commodities possible, to introduce a subdivision of "potential ores." For example, there are many mineral masses not exploitable at present yet exploitable under conditions only slightly better. Some may have been sporadically worked in the past under exceptional conditions. Following the economist's terminology, we might refer to these as "marginal" resources. Beyond the "marginal" deposits are those masses that require conditions even more favorable but still, in the opinion of the miner and the metallurgist, within reach, and to these we assign the term "submarginal" resources, again using a term fixed in both mining and economic terminology. The rest—that part of the "potential ores" that may be exploited in the more distant future of the economist—we propose to call "latent" resources.

Equation (1) then becomes

$$\text{Resources} = \text{reserves} + \text{marginal resources} + \text{submarginal resources} + \text{latent resources} \tag{2}$$

The appraiser can be guided either by equation (1) or by equation (2) depending upon the information available to him and upon the purpose of his appraisal.

Naturally, a deposit or a mineral mass does not have a fixed quantity in one or another of these four categories of resources, or fixed ratios among them. As economic conditions and technology improve, or as more is learned about the deposit, a particular mineral mass or parts of it may very well pass from a lower category to a higher one.

The opposite is also possible, though less likely—that is, material may pass from a higher category to a lower one. For example, the low-grade residue in the native copper deposits of Michigan in the United States is a "marginal resource," but if there occurs the secular increase in general costs that some economists envision, without a corresponding increase in the price of the metal, this material may become "submarginal"; and if the mines should be shut down and the equipment be withdrawn, this material may even cease to be considered a resource at all, as has happened at other mines.

This kind of situation emphasizes the restrictions we would place on the term "reserves." We think that masses or deposits susceptible to profitable exploitation only during periods of high prices should not be considered as constituting "reserves"—not even during the period of exploitation—but only as "marginal resources." In doing this we reason partly as does the miner himself, partly contrary to him. A future exploitation is normally not based on possible exceptional high markets, but on average prices stretched out over a period. If a mineral mass is exploitable at the present time only because of

exceptional market prices, it should not be considered a genuine "reserve" until average market values become sufficiently high for exploitation to continue as a matter of course.

Classification of reserves

When the miner estimates reserves he needs a classification that meets three specifications:

(1) It will provide as nearly as possible a positive measure of the quantity of ore or metal he can rely upon, at least the minimum necessary in making his plans as a businessman.

(2) It will provide as nearly as possible a standard procedure for estimating this minimum quantity, and

(3) It will provide a way of expressing the inherent geologic uncertainties.

The miner's usual classification is of *proved, probable,* and *possible* ore, in decreasing order of certainty. It is impossible to get a common definition of these terms. Authorities seem never to have agreed, a fact that reflects the difficulty of defining reserves in a way that will satisfy all or most conditions of mining and all or most kinds of deposits. The following definitions represent our understanding of the way the terms are most often thought of:

Proved ore (positive ore, blocked-out ore, assured ore). Ore exposed on three sides and where there is, therefore, practically no risk of failure of continuity.

Probable ore. Ore exposed on two sides and where there is, therefore, some risk, yet warranting reasonable assumption of continuity.

Possible ore (prospective ore). Ore that cannot be included in the above classes but the presence of which can be reasonably expected, because of exposure by a shaft or drift or bore hole, or for some geologic reason.

These definitions lean strongly toward the rigidly geometric, and various modifications of them have appeared from time to time in order to introduce the geologic factors more adequately. Definitions that meet the specifications outlined above have been given by Leith (9) and we recommend their common acceptance. They are as follows:

Proved or assured ore. Ore blocked out in three dimensions by actual underground mining operations or by drilling, but it includes in addition minor extensions beyond actual openings and drill holes, where the geological factors that limit the ore body are definitely known and where the chance of failure of the ore to reach these limits is so remote as not to be a factor in the practical planning of mine operations.

Probable or semiproven ore covers extensions near at hand, where the conditions are such that ore will probably be found but where the extent and limiting conditions cannot be so precisely defined as for proved ore. Semiproven may also mean ore that has been cut by scattered drill holes, but too widely spaced to assure continuity.

Possible ore. Ore is classed as possible or prospective where the relations of the land to adjacent ore bodies and to geologic structures warrant some presumption that ore will be found but where the lack of exploration and development data precludes anything like certainty of its actual location or extent. Often it is not desirable to assign figures to "possible" tonnages, but they may be designated by terms like "small" or "large."

But this classification applies only to the need of the miner. There is also needed a classification for the man who would assess the present reserve position or the resource position of a whole industry or of a region or a nation. Such assessments are composed of a summation of estimates of individual mines and districts, expanded by geologic and economic judgment. They are made not by the miner, but by civil servants or others who are not privy to the reserve estimates for individual mines. Moreover, in making them it is not necessary that the data on any single deposit be as well measured as for estimating proved or probable ore—indeed, such data are rarely extant for the undeveloped deposits. The need in the national appraisal is not for accurate measurement, but for an appreciation of magnitude.

For this purpose, the staffs of the United States Bureau of Mines and the United States Geological Survey, in assessing the mineral position of the United States in 1944 (13) used the classification of *measured, indicated,* and *inferred* reserves. In fact, they were forced into creating a new classification because the Government exploration rarely yielded the geometric information needed to estimate reserves as proved or probable. The definitions of the terms are as follows:

Measured reserves are those for which tonnage is computed from dimensions revealed in outcrops, trenches, workings and drill holes and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling, and measurement are spaced so closely and the geologic character is so well defined that size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to be different from the computed tonnage or grade by more than 20 percent.

Indicated reserves are those for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurement, and sampling are too widely or otherwise inappropriately spaced to permit the mineral bodies to be outlined completely or the grade established throughout.

Inferred reserves are those for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition, of which there is geologic evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred reserves should include a statement of the specific limits within which the inferred material may lie.

As may be noted, these categories are analogous to *proved, probable* and *possible,* but they are too general and have too large a margin of error to satisfy the practical business needs of the miner.

These new definitions are being found so useful that they are creeping into worldwide acceptance. We propose to accept the concept, modifying it in one way.

As mentioned above, estimators of national reserves or resources commonly do not have access to the estimates of ore reserves of individual companies. Such information is jealously guarded. Accordingly, in practice the estimator cannot separately assess "measured" and "indicated" reserves but

must combine them into a single figure, and indeed he finds it no detriment to his purpose to do so. The "measured" reserves do not constitute or express a characteristic of the deposits of a district or of a nation but represent only the bulk sentiment of mine management as to how thoroughly a deposit should be developed before mining is started—indeed, they commonly represent only the bulk sentiment of the first entrepreneurs, grown into a tradition through the practice of attempting to find each year as much ore as was mined out in that year, as discussed in more detail farther on.

We suggest, therefore, that the terms "measured" and "indicated" be abandoned and be replaced by a single term that will include them both. For want of a better we suggest "demonstrated" reserves, in contradistinction to "inferred" reserves. Thus, we may say we have "demonstrated" the existence of a hundred million tons of reserves, for example, without having "measured" them. The proposed definition of demonstrated reserves is as follows:

> *Demonstrated* reserves are those for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on geologic evidence. They may include some orebodies concerning which the sites for inspection, sampling, and measurement are spaced so closely and the geologic character so well defined that size, shape, and mineral content are well established, and other orebodies concerning which the sites available for inspection, sampling, and measurement are too widely or otherwise in appropriately spaced to permit the bodies to be outlined completely or the grade established throughout.

PERIODIC REVIEW

Clearly, estimates of reserves and resources, and especially their division into categories, are never final. With changes in economic conditions, some resources will go from a less favorable to a more favorable category, or vice versa. A growing part of the reserves will disappear through exploitation. Within the "reserves," better knowledge acquired through new mining works will allow a "possible" or "inferred" part to pass on to a more certain category. This may happen even through nothing more portentous than increased availability of information already in existence. Finally, entire estimates may be revised through a better geologic or mining or economic appreciation.

The estimates are entirely valid only for the date on which they are made and must be reviewed periodically. This is common practice in mining circles in estimating reserves; it now happens only incidently in appraising resources.

FURTHER CONSIDERATIONS

In order not to complicate the discussion, we have reasoned up to now that the miner and the economist are interested in knowing that such and such a deposit, or that such and such a region, contains X million tons of ore. That is true, but he would like, if possible, to know much more. He would like, in fact, to be able to say: This deposit—or this region—is likely to produce Y million tons annually over a period of Z years.

The miner is fortunate in this regard, for he himself ordinarily decides the annual production of the deposit with which he is concerned. Both the life and the annual production are conditioned not only by the technical characteristics of the deposit, but also by the market possibilities, by the profit per ton or other unit and the necessity of a sufficient annual production to meet the financial burden, by the level of income the miner desires, and by the number of years over which he wishes to amortize the investment. At the outset, he will "prove" the reserves only to the extent necessary to support production at the desired rate for the number of years desired for amortization; afterwards, each year he will try to "prove" new reserves equal to the tonnage extracted during the year, rarely at a greater rate unless he can do so in quantity sufficient to expand the annual rate of production profitably. What he does not and cannot know is how long he can perpetuate his operations in this fashion.

The economist is in a similar quandary. He may know, for example, that a country contains ten billion tons of iron ore, which at present rates of production would last, say, a thousand years, and he contents himself with this information because he has no other. But what he would really like to know is how much the country would be able to furnish annually under the various economic conditions that he cares to postulate.

The statement that a country has a specified number of years of reserves of a metal at present rates of production seems precise, but in reality it is meaningless as a measure of reserves or resources because it makes no allowance for the fact that production rates do not remain constant—the production for any particular year or period is likely to be a unique quantity—or for the effect of depletion on the one hand or new discovery on the other.

CONCLUSION

Simple knowledge of the mineral resources of a mine or region, however categorized, is only partial information on what could be called the ultimate possibilities of the mine or region. Yet such information is about all that we, as geologists and engineers, are in a position to furnish. All the more reason to try to clear up the ambiguities surrounding it. Such is the aim of this report.

In so aiming, we have indicated the different, yet supplemental, ways in which the mining man and the economist approach the matter of mineral resource appraisal, and have indicated the differing needs of each; we have made a distinction between reserves and resources and have shown the relation of one to the other, offering definitions for each; we have recommended common acceptance of specific definitions of *proved*, *probable*, and *possible* ore as applicable to the needs of the miner, and have recommended definitions of *demonstrated* and *inferred* reserves as meeting the needs of the man who would assess the reserve or resource position of a whole industry or of a region or a nation. And finally, we have pointed out the necessity of periodic review of any and all estimates of reserves and resources because of the unique changeability of the factors that condition such estimates. We cannot

emphasize too strongly the necessity of specifying the limiting factors or assumptions in any estimate of reserves or resources, such as cut-off value, for example, or some particular technology. The benefit of more definite concepts and of commonly accepted definitions will be partly offset if ambiguity persists through failure to state the assumptions controlling the estimate.

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ORIGIN OF THE BEDDED MAGNESITE DEPOSITS OF MANCHURIA

HIRONAO NISHIHARA

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ABSTRACT

The classical theory, of the origin of the Manchurian magnesite by hydrothermal processes, does not accord with observations on the geochemistry of magnesium. Field observations and chemical experiments suggest that the magnesite was deposited directly from the waters of Precambrian seas.

INTRODUCTION

CONTROVERSIAL discussions resulted from a paper by Dr. K. Niinomy (54) and one by the writer (56) on the magnesite deposits of Manchuria. Niinomy, supported by the late Dr. T. Kato (34), maintained that the Manchurian magnesite was formed by the replacement of calcium in dolomite by magnesium from magmatic water that emanated from intrusive biotite granite. The writer has maintained the opposing view that the magnesite was precipitated with the dolomite in a Precambrian lagoon or shallow sea. A proper understanding of the genesis of these deposits is needed to guide the search for similar deposits elsewhere.

Following the classical theory of the igneous origin of certain ore deposits the writer, on his first examination in 1915, nearly concluded that this magnesite was of igneous origin. However, repeated examinations of the deposit,

which extends northeastward for sixty kilometers beyond the original discovery, revealed features that did not accord with the classical theory. These features include the relation of the magnesite deposits to regional and local geology, the stratigraphic relationships among the carbonate sediments, the structural relationship of the sediments to the granite and, finally, the immense size of the magnesite deposits.

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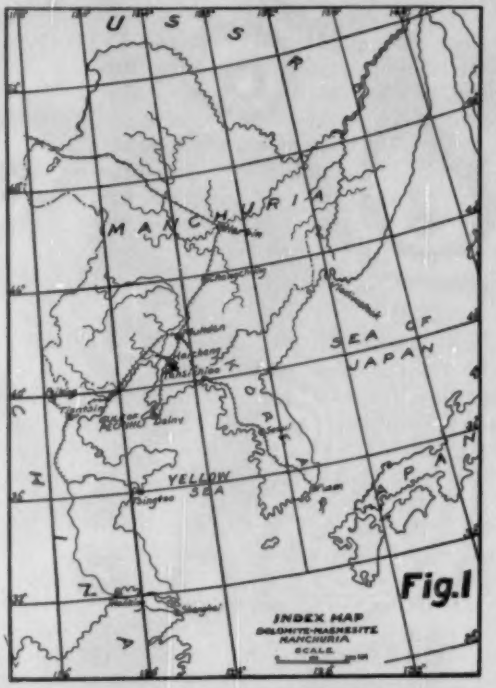

Fig.1

at that University for direction and council and for laboratory and library facilities. In Japan, it is a pleasure to acknowledge the generous cooperation of Professor Rinji Saito and the help of Dr. Ryuji Endo whose extended Precambrian studies established the stratigraphic correlation of the Manchurian magnesite and dolomite.

LOCATION

The district is at Latitude 40° 40′ N, Longitude 122° 30′ E, in the southwestern part of old Manchuria close to the northeastern corner of the Gulf

of Pechili, the mouth of Liaoho river and the mid point between Port Dalny and Mukden (Fig. 1). The dolomite-magnesite range starts at Tahsichiao and, gradually rising to an elevation of 600 meters, extends northeasterly at least 60 kilometers to Wankancheng. The average width of the range is three kilometers.

Discovery and Exploration of Magnesite.—In 1913 crystalline magnesite was discovered near Tahsichiao and extraction was started by the South Manchuria Railway Company. Previously, coarsely crystalline magnesite, such as this Manchurian material, was almost unknown.

A small pilot plant started calcining the magnesite at Tahsichiao about 1922. As the demand increased eight plants were installed and by 1938 the monthly production of magnesia clinker exceeded 10,000 tons. Some of the coal used to make coke for primitive kilns contributed silica to the final product. Consequently this product, although accepted at the Japanese steel mills, could not compete on the world market. Such competition could have been met, however, by installing more modern, gas-burning kilns.

There appears to be no available record of total magnesite production, all of which came from Tahsichiao, near the southwestern end of the dolomite-magnesite range. The ore reserve, estimated by the writer in 1939, is over 30 billion tons containing 47 per cent MgO.

REGIONAL RELATIONS

Geography.—Manchuria is separated from Soviet Russia by the Heilungkian River, and from eastern Siberia and the Mongolian desert by the Tahsinganlin range which rises in the northwest corner of Manchuria and runs south and southwest into China. Along the coast, facing the Japan Sea, mountains averaging 600 m in height trend from northeast to southwest forming the backbone of Eastern Manchuria. Between the two highland areas, and extending parallel with them, is a river-washed lowland. The principal topographic grain, then, is northeast-southwest; the rivers in part follow this grain, in part flow northwest-southeast.

Manchuria is semi-arid. Only the Tahsinganlin and Hsiaohsinganlin ranges are thickly wooded. The yearly climatic changes are extreme.

The mineral resources are few and include coal, low-grade iron ores, dolomite, magnesite, and talc. From ancient times placer gold has been produced in northern Manchuria along the Zdungalee River, and a few old gold-quartz mines in Je-hol Province were reopened by the Japanese. The total gold production, although unknown, is probably very large.

Geology.—A reconnaisance of south Manchurian geology was made in 1869 by von Richthofen, and Blackwelder (3) visited this part of Manchuria in 1903. After establishment of the Geological Survey division of the South Manchuria Railway Company some 50 years ago, geological mapping was begun in southern Manchuria and for 40 years was gradually extended into the remote northern region. Agreement is not general about age assignments and correlations, but the outline of Manchurian geology appears to be as follows:

The Archaean basal complex, granite gneiss and biotite schist—the Sankan formation of von Richthofen—is expressed in the Tahsinganlin and Hsiaohsinganlin ranges of western and northwestern Manchuria, and in Je-hol Province to the south. The general trend is northeast-southwest into the Chinese Sankan (Taishan complex of Willis and Blackwelder) in the Shantung Peninsula.

According to Grabau (*27*) a long, narrow seaway began to grow northeastward at right angles to the Himalayan geosyncline in the late Precambrian, and by Cambrian time had connected with the Arctic Ocean. Long-continued erosion of the borderland resulted in deposition in this trough. The first sediments, now strongly metamorphosed, made up the Wutai system assigned by Grabau to the Proterozoic, by Endo to Upper Archaean. Both authors described highly magnesian carbonate sediments in the Wutai. It seems that Wutai sedimentation was interrupted by one or more episodes of folding and granitic intrusion.

Geosynclinal sinking and sedimentation were continued in Sinian time (Late Precambrian, Grabau; Late Precambrian, Endo; Cambrian and Ordovician, Willis and Blackwelder). The sediments were like those of the Wutai system and there was extensive development of dolomite and magnesian limestones with reefs of calcareous algae, some of which are as young as basal Devonian. The thickness of sediments from basal Sinian to basal Devonian is nearly 4,000 m.

There were intrusions of peridotite and diabase in Carboniferous time, but in general slow uplift and deposition in inland lakes and seas prevailed between the Ordovician and the Triassic when, principally in northern Manchuria, the sediments were intensely folded and granitic rocks were intruded.

In Cretaceous time the Yenshan orogeny, starting in China, extended into Manchuria, attended by intrusion of various igneous rocks. The Tertiary Himalayan orogeny also extended into Manchuria, where the adjustments were expressed as tension faults.

The most significant features of the geologic history are the northeastward extension of the Himalayan geosyncline into Manchuria, beginning in late Precambrian time, and repeated deposition therein of magnesian carbonate sediments. These magnesian sediments were deposited from southern China far into Manchuria as a linear belt several thousand kilometers long. From time to time an inland sea, remote from the open ocean, with coastal lagoons and protecting barriers, may have existed. This could have happened whenever sedimentation began to overtake the very slow downwarping. In such lagoons magnesian sediments may have accumulated.

GEOLOGY OF THE DOLOMITE-MAGNESITE AREA

The floor of the Himalayan geosyncline in this area should be granite gneiss and granites corresponding to the Chinese Sankan. The writer thinks that the gneissic granite (Ge on Saito's geological map, Fig. 2) is part of the Archaean complex, or floor of the geosyncline. Saito, however, regarded this

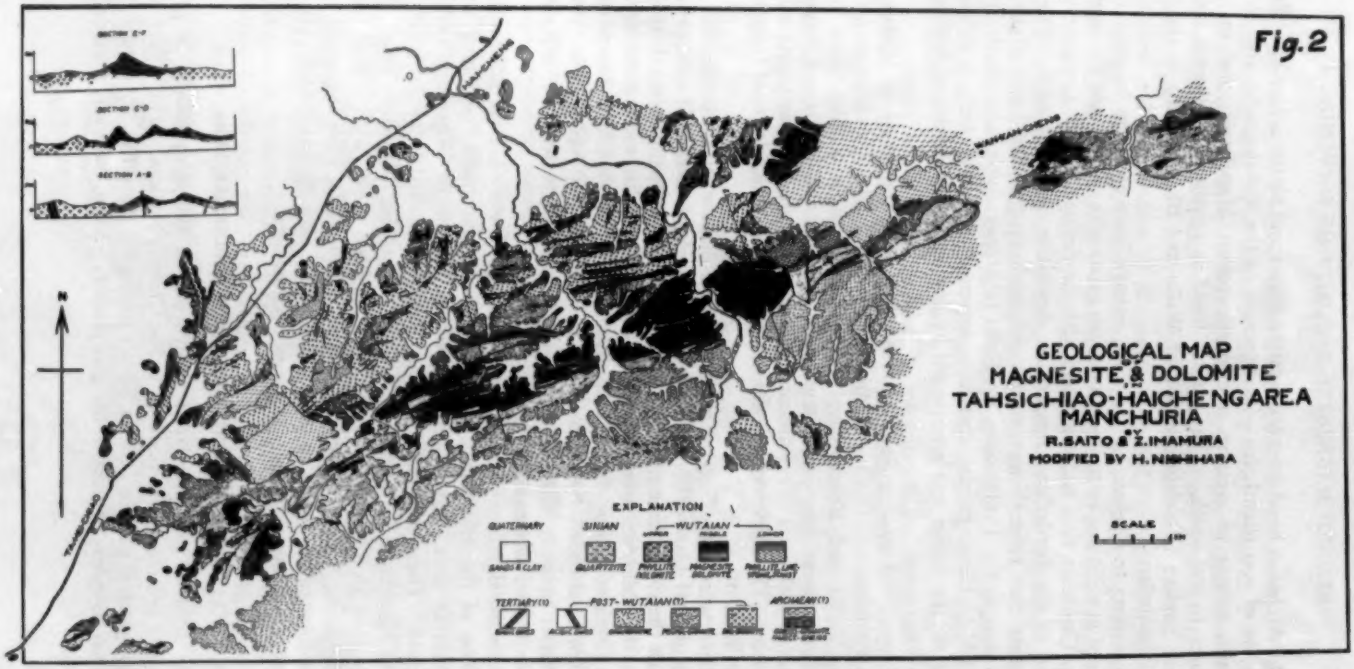
Fig.2
SECTION C-C'
SECTION D-D'
SECTION A-B
N
GEOLOGICAL MAP
MAGNESITE & DOLOMITE
TAHSICHIAO-HAICHENG AREA
MANCHURIA
R. SAITO & Z. IMAMURA
MODIFIED BY H. NISHIHARA
EXPLANATION
QUATERNARY
SINIAN
WUTAIAN
SCALE

gneiss as intrusive into the lower Wutai. Associated with this gneiss is biotite granite, also regarded by the writer as part of the Archaean complex.

The lower Wutai (Liao-ho of Saito) here consists of phyllite, limestone and mica schist and is followed by the dolomite-magnesite series (middle Liao-ho of Saito). Apparently Saito's upper Liao-ho is lower Wutai (Liao-ho), so that the areas of biotite granite that at first sight appear to intrude the upper part of the Liao-ho series are actually parts of the Archean floor disclosed by erosion. At one place, indeed, the magnesian rocks themselves were seen resting unconformably on an eroded surface of granite. It seems, therefore, that the biotite granite and granite gneiss are definitely older than the dolomite-magnesite sequence.

Interfingering with the dolomite-magnesite series on the seaward side, and finally overlying the carbonate rocks, is a fine-grained quartzite that may have formed sand barriers behind which the carbonate sediments accumulated. This quartzite is ripple-marked, and is overlain by iron ores in the Anshan district to the north.

The folding, thrust faulting, and metamorphism of the rocks may have been effected by the late Cretaceous Yenshan orogenic movement. At this time, perhaps, dikes of granophyre, granite pegmatite, hornblende porphyry, and quartz porphyry intruded the older granites and the Wutai sediments. Certain chlorine- and fluorine-bearing minerals, sparingly present in the schists and carbonate rocks, may be genetically related to these dikes.

After the intrusion of these dikes, transverse, NW-SE faults divided the folded and thrust faulted zone into several blocks.

The absence of Cambrian and later sediments in the area may be the result of denudation that stripped away several thousand meters of overlying strata and laid bare the Wutai system with the dolomite-magnesite series. These Precambrian sediments now lie in an elongated syncline between parallel, northeast trending ranges.

The dolomite extensively developed in the area overlies the lower Wutai. It is bedded, and the chemical composition is fairly uniform throughout. The magnesite (Fig. 2) is interbedded with the dolomite.

The contact between dolomite and magnesite is not in all cases obvious. At many places, along the contact, dolomite and magnesite crystals of same color interlock. At such places the contact can be located by chemical analyses. At many other places, thin layers of silica-, magnesium-, iron- and manganese-bearing schist separate the dolomite from the magnesite.

In the crystalline magnesite itself no lenses of schist are found, but south of Haicheng, thin dark grey bands, 5 to 10 mm thick and 3 to 5 m. long occur at intervals of 4 or 5 cm in three or four horizons. Chemical analysis shows this dark grey material to be a hydrous magnesium silicate. Some of this silicate (talc) is present locally on the dolomite-magnesite contacts, always on the magnesite side. These bands appear to represent impurities of some sort, precipitated at the beginnings of cycles of magnesite deposition.

The magnesite is bedded, and varies somewhat in color, being locally white, grey or pink. It is generally coarsely crystalline (maximum crystal diameter

4 cm) and locally saccharoidal. At some places, for example, south Haicheng, the thickness of the bedded magnesite may exceed 300 m.

POSSIBLE SOURCE OF MAGNESIUM

Magmatic Source.—According to Clarke (9) the average igneous rock contains 2.09 percent magnesium or 3.49 percent magnesia. Magnesia is used up in the crystallization of olivine, the pyroxenes, amphiboles, and finally biotite. Therefore, crystallization should deplete the magma of magnesia rather than store magnesia in the final fractions. This expectation is realized in the relatively low magnesia content of the siliceous rocks as compared with the mafic rocks richer in the first crystallized constituents.

It would seem, then, that the residual fluids, gases or liquids, from the crystallization of magma would carry little or no magnesium. Zies (87) reported no magnesium in either the exhalations or the incrustations at the Valley of Ten Thousand Smokes. Analyses by Gautier (22–24), Day and Shepherd (14), Moissan (50–51), Bunsen (7), Sainte-Claire Deville and LeBlanc (70), Silvestri (75), Fouqué (19–20) and those reported by Brun (5) likewise reveal no magnesium in volcanic or fumarole gases. Tilden (81), Chamberlin (8), and Gautier (22–24) have analyzed the gases obtained by heating igneous rocks and report no magnesium in these gases. It appears, then, that magnesium is not present in the gases given off by crystallizing magma. Perhaps the magnesium is given off at a final stage in aqueous liquid solution.

Analyses of "juvenile" waters from thermal springs are subject to the criticism that the hot water, even if truly juvenile, may have dissolved certain substances from the walls of the passages. In any case, analyses of waters believed to be juvenile show magnesium salts in amounts that rarely reach 16.45 percent of total salts, or about 0.06 gram of magnesium per cubic meter of water. Other salts, some of them less soluble than the magnesium ones, are generally present in equal or greater amounts. In no case are the magnesium salts exclusively present.

Using the very highest values, approximately 5×10^{17} cubic meters of juvenile water would be required to convert 30 billion tons of Manchurian dolomite into magnesite. Assuming the highest permissible water content, an incredible volume of magma would be required. If these considerations do not preclude magma as a direct source of magnesium for the Manchurian magnesite, they surely cast serious doubt on such a source.

Ocean Water.—Clarke (9, p. 23) on the basis of data collected by Ditmar (15) calculated the magnesium salts to be 15.84 percent of all ocean salts, and magnesium to constitute 0.14 percent of the ocean water. Magnesium is 3.771 percent of the ocean salts, and as the salinity of the ocean averages about 3.5, magnesium is present in amount sufficient to cover the United States, excluding Alaska, 317 feet deep. This great store of magnesium must have accumulated mostly from the destruction of magnesium-bearing rocks and minerals, and magnesium salts must have been transported to the sea by streams.

River Waters.—Many analyses (9, p. 127) show the salinity of river waters to vary from about 14 to more than 1,500 parts per million, and in the dissolved salts magnesium varies between 1.22 percent and 10.71 percent. Again, it is obvious that a great volume of water is required to furnish much magnesium, but erosion and transportation are continual.

If, in seeking the source of the magnesium in the Manchurian magnesite, one turns to the contributions made by rivers and stored in the ocean, he is confronted with the problem of the precipitation of magnesium from sea water.

PRECIPITATION OF MAGNESIUM SALTS

Next to magnesium quantitatively in sea water is calcium, but calcium greatly exceeds magnesium in the waters of most streams. Because calcium carbonate, under most natural conditions, is less soluble than magnesium carbonate, the chemical marine sediment is generally limestone. Thus is explained the excess of magnesium over calcium in the sea. Some uncommon condition is necessary to precipitate the magnesium of sea water as carbonate —that is, as dolomite or magnesite. Wattenberg (84) concluded that, although magnesium carbonate is less soluble in sea water than in fresh water, and although about three times as much magnesium as calcium is dissolved in the sea, sea water is not saturated with magnesium carbonate. Because magnesium hydroxide is more insoluble than calcium hydroxide, the magnesium may first precipitate as the hydroxide, change later to the carbonate. Further, the precipitation may be direct, or it may involve replacement of calcium carbonate.

Experimental Precipitation of Dolomite.—Several investigators obtained dolomite at temperatures much higher than those commonly found in the sea; hence their results have little bearing on the present problem. Klement, (36) using a concentrated solution of magnesium sulphate at 60°, was able to replace aragonite rapidly but partially by dolomite. He suggested that dolomite might form in closed lagoons by reaction of the saline-saturated water with the aragonite of coral reefs. Pfaff (65) obtained dolomite by passing a current of carbon dioxide slowly through a warm solution of sulphates and chlorides of magnesium and calcium and evaporating at 20° to 25° C.

Linck (42) by adding calcium chloride solution to a mixed solution of magnesium chloride, magnesium sulphate, and ammonium sesquicarbonate, and gently heating in a closed tube, obtained crystals that proved to be dolomite chemically and optically. He concluded that dolomite may never form in the open ocean, but in warm, shallow seas in the presence of ammonium salts derived from the decomposition of organic matter.

Previously (43, 44), he had suggested that dolomite formed by the replacement of calcareous sediments in the presence of ammonium carbonate at but slightly elevated temperatures and pressures. Kohler (38) could make dolomite from $MgSO_4$ only in the presence of $(NH_4)_2SO_4$.

Krotov (39) Found that the Heidinger reaction,

$$2CaCo_3 + MgSO_4 \rightleftharpoons CaCO_3 \cdot MgCO_3 + CaSO_4$$

is prevented from going to the left if the solution is concentrated and is saturated with NaCl.

Bar (2) found that the pressure of CO_2 is important. Above $PCO_2 = 20 \times 10 - 4$ atm., $CaCO_3$ is more soluble than $MgCO_3$ and vice versa. Udluff (83) constructed curves illustrating these relations.

Some writers have emphasized the function of hydrogen ion concentration, pH. Mitchell (49) obtained $CaCO_3 \cdot MgCO_3 \cdot H_2O$ by adding $MgCl_2$ and a solution of $CaHCO_3$ to artificial sea water at pH 7 to 9. Teodorovich (80) found that with an increase in magnesium content and a rise in temperature dolomite would form from sea water at a pH not higher than 8.1. The work of Krumbein and Garrels (40) suggests that the deposition of dolomite and magnesite will require a pH higher than 7.

Experimental Precipitation of Magnesium Hydroxide and Carbonate.—If magnesium carbonate is precipitated directly from sea water, as some observations (78) seem to prove, the conditions under which this deposition takes place appear to be even more restricted than those that govern the formation of dolomite. There appear to have been no experiments that resulted in the deposition of anhydrous $MgCO_3$, but magnesium hydroxide and the hydrous carbonate have been formed.

Klyachko and Kondratyuk (37) obtained a hydrophobic precipitate of $Mg(OH)_2$ when NaOH solution was added to $MgSO_4$ solution, and a hydrophilic precipitate in the presence of excess OH^-. Rankama and Sahama (66) suggest the precipitation of magnesium from sea water as the hydroxide. The patented process of Closs and Baker (10) suggests how the hydroxide may be converted to the carbonate in nature by the action of CO_2.

Lucas (48) precipitated aragonite by the addition of amine carbonate to sea water at pH 7.8; nesquehonite ($MgCO_3 \cdot 3H_2O$) at pH 8.5. Halla (29) precipitated $MgCO_3 \cdot 3H_2O$ by adding solutions of calcium salts to solutions of $Mg(HCO_3)_2$. It is probable that once the hydrated carbonate forms in nature, it would recrystallize to the carbonate with loss of water.

The formation of magnesite from dolomite, either by the leaching of calcium, or replacement of calcium by magnesium, has been suggested. Perhaps this mode of origin can not be precluded for the Manchurian magnesite, but no supporting evidence is known.

ENVIRONMENT OF DEPOSITION OF NATURAL MAGNESIUM CARBONATES

The experiments mentioned above suggest that the features favoring the precipitation of magnesium in the sea are, (1) an increase in the concentration of magnesium sulphate, (2) saturation with sodium chloride, (3) the presence of ammonium, or organic, salts, (4) a pressure of CO_2 above 20×10^{-4} atm., (5) a pH greater than 7, and (6) some rise of temperature. Excepting the relatively small amount of dissolved CO_2, the restricted arid

environment of Krumbein and Garrels (40) most nearly meets these conditions. That is, the deposition of magnesium carbonates would seem to be especially favored in lagoons in a warm, arid or semi-arid climate. According to Twenhofel (82) most dolomitic limestones have been deposited in lagoons or narrow sea embayments so shallow that the bottoms at times were exposed and mud cracks developed. Barriers built up on the seaward side by waves protect the lagoonal sediments.

Strakhov (78) studied carbonate formation in lagoonal environments, and recognized two types. In the Azov-Black Sea type the alkalinity varies little with the salt content. There calcium carbonate is deposited almost exclusively. In the Ural-Caspian type alkalinity varies sharply with the salt content. The pH at first is about 8 and drops to 7.4 as the salt content increases. The first sediment is calcium carbonate and at higher salt concentration contains magnesite in addition to calcite. With further decrease in alkalinity $CaSO_4$ precipitates. Under present conditions, only gypsum, calcite, and finally magnesite, form. It is known, then, that in those environments that approach the ones suggested by experiments some dolomite and magnesite is precipitated today.

FIELD STUDIES OF MAGNESIUM CARBONATES

Much evidence indicating the replacement of limestone by dolomite is given in the literature, but there is also evidence that suggests the direct precipitation of dolomite. Dolomitization usually results in the complete or partial destruction of sedimentary structures, including fossils, but Nehaeva (53) described dolomites with algae in the Middle Cambrian limestone-dolomite formation in the basin of the Ida and Ossa rivers, Angara. Fossils were found by Lammermayer (41) in the magnesite deposits at Dienten (Salzburg). According to Grabau (27) the dolomitic Nankou limestone contains abundant algae that appear to have been the chief, if not the only, source of the calcium-magnesium carbonate.

Pfaff (65) concluded that the dolomite in the Seine bank formation of France had formed partly by direct precipitation from sea water and partly by replacement of calcium by magnesium during reaction with magnesium salt solutions. Judd and Skeats (33) thought that the dolomite at Funafuti was precipitated along with calcite and aragonite from sea water, but David (13) found that dolomitization of the reef was apparent from the surface downward and was complete at a depth of 60 feet. Longwell (47) has described a thinly laminated, mud-cracked sediment in the Tertiary Horse Spring formation. The sediment consists of dolomite, clay, silt, gypsum and tuffaceous beds.

Gale (21) described a commercially exploited magnesite deposit near Bissel, California, as a sediment formed by direct precipitation. He inferred that magnesian solutions, probably the sulphate, precipitated magnesite by reaction with solutions containing sodium carbonate.

According to Dunbar (16) the Miocene deposits of southern Nevada begin with thick, coarse conglomerates, overlain by clays and silts that include thick

beds of gypsum, magnesite, and borax. These deposits formed in arid basins of interior drainage, under conditions that approach those believed to control the formation of marine magnesite.

Joaquin Gomez de Llarena (46) described a magnesite deposit in the upper valley of the Arga (Pyrenees of Spanish Navarro). This deposit is associated with limestone and dolomite, interbedded with schist and greywacke. The well crystallized magnesite is considered to be of lacustrine origin by direct precipitation. The surface of the magnesite and associated deposits is ripple-marked. There is no evidence of progressive dolomitization, and the boundary between magnesite and sterile rock is sharp.

SUMMARY AND CONCLUSION

The crystallization of igneous rocks appears to use up the magnesium of the magma, so that little, if any, magnesium remains in the final residue.

Chemical analyses have shown that magnesium does not occur in detectable amounts in the gases of volcanoes or fumaroles or in gases occluded from igneous rocks. Further, analyses of waters believed to be juvenile reveal very minor amounts of magnesium, part or all of which could have been derived from the walls of channelways. For these reasons the magmatic origin of any very large magnesite deposit in sediments is seriously questioned.

In the case of the magnesite deposits of Manchuria, the largest near-by masses of igneous rock, the granite gneiss and the biotite granite, are definitely older than the magnesian sediments, and the small dikes are much younger than these sediments. Even so, it is possible that emanations derived from underlying intrusions could have robbed certain magnesium-bearing rocks and so have formed the magnesite by selective reaction with certain favorable dolomite beds. Evidence to support such a theory seems to be lacking, however, and the very immensity of the magnesite deposits retards acceptance of the theory.

It is well known that the weathering of magnesium-bearing rocks has always contributed to the store of magnesium salts in the sea, and so far as known this store has always been available provided that the conditions favoring precipitation of magnesium could be met.

Although existing data are admittedly inconclusive, it seems that magnesite will precipitate under the conditions discussed above in partially enclosed lagoons in a warm, arid or semi arid climate. The writer feels that, rather than postulate a magmatic origin, which is purely speculative, or support a modified hydrothermal theory, for which evidence seems lacking, it is better to accept the incomplete evidence afforded by regional and local geology, chemical analyses and experiments, and observations on naturally occurring magnesian carbonates. Accordingly, the store of magnesium salts in the sea is suggested as the source, and primary deposition as the process.

In putting forth this suggestion the author makes no claim to finality. Let others, working with this and similar problems, weigh the evidence for

themselves to see how the idea of primary deposition balances with other theories.

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SCIENTIFIC COMMUNICATIONS

ABBREVIATIONS IN FIELD AND MINE GEOLOGICAL MAPPING

F. M. CHACE

INTRODUCTION

Symbols and abbreviations are widely used in surface and underground geological mapping and notetaking. A standard set of symbols has gradually evolved so that members of the U. S. Geological Survey and the staffs of many mining companies and other organizations use essentially the same ones (1).* A set of abbreviations, however, has never been generally adopted. Numerous textbooks contain brief lists of suggested word contractions, and the geological staffs of various mining companies have adopted abbreviations for their own particular use; but with the exception of a few common terms, such as "ss" for sandstone and "vn" for vein, there is little uniformity in usage. The first extensive list of abbreviations known to the writer was compiled for the use of the Secondary Enrichment Research Group under L. C. Graton (circa 1914). This pertained to minerals only and, although widely used by that group, did not come into general usage. The most comprehensive list that has been published was prepared by a committee of the American Mining Congress in 1924 for use in underground geological mapping (2). This list has had varying degrees of acceptance, but in general is not well known.

A standard set of abbreviations of the more common geologic terms generally understandable and acceptable to all is highly desirable. The accompanying lists have been prepared in the hope that their publication may result in discussion leading to a standard set generally acceptable. For several reasons this will probably be even more difficult to achieve than was the list of symbols. Nearly every field or mining geologist has a set of favorite abbreviations that he has accumulated from his student days and would give up with reluctance; moreover, it is easy to improvise as the need arises. Such abbreviations may or may not be intelligible to other geologists, and in any event, little uniformity in usage can be found.

The following lists of abbreviations are included in this compilation:

Rocks
Minerals and Metals
Colors
Grain Size
Descriptive and Structural Terms
Surveying and General Science

* References at end of paper.

In compiling the lists, a large number of references has been examined, and many colleagues on the staffs of mining companies, universities, and the U. S. Geological Survey have been consulted.[1]

The lists prepared by P. D. Wilson for the Committee of the American Mining Congress in 1924 (2) and the mineral abbreviations used by the Secondary Enrichment Research Group have been used as a basis for the present compilation and as establishing a precedent to be followed in case of conflicts. The abbreviations and symbols used in the list entitled "Surveying, Measurements and General Science" were largely gathered from the long list published by the Committee on Abbreviations of the American Standard Association (3).

FUNDAMENTAL RULES

Abbreviations are normally made in two ways:

(1) The first letter of the word is given and at any place thereafter (after one letter, after two letters, etc.), it is cut short with a period; e.g., N. = North, syn. = syncline. The full stop is commonly omitted in mathematical abbreviations such as sine = sin, cosine = cos, etc., and between letters such as USGS, NRA, WPB.

(2) A part of the middle letters of the word is dropped out, with the first and last letters retained with or without others between; e.g., wt = weight, hrs = hours. A period is not used as it is usually clear that the letters are abbreviations of a full word. A mixed class is also used in which the period at the end indicates the final letters of a word are missing, but without implying (as in 1) that all the letters up to that point are present; e.g., cg. = centigram, avdp. = av(oir)d(u)p(ois) (6).

These general rules have been followed in the preparation of the accompanying lists. However, because of lack of precedence in many instances and the very strong personal element involved, any list of geological abbreviations must necessarily be somewhat arbitrary. Moreocer, because of the many words in the general vocabulary and the many technical terms used in geology, it is almost impossible to avoid conflicts and repetitions. With these difficulties in mind, several more or less obvious rules and suggestions for the preparation and usage of abbreviations of geological and technical terms are given below:

1. Abbreviations should be as concise as possible. Two letters are preferable for clarity and conciseness; three may be necessary to avoid conflicts and repetitions. Use of one letter, such as "p" for porphyry, should be avoided as too indefinite. To abbreviate a long word, a simple contraction is possible by leaving out the vowels. Example: sheeting—"shtg". An acceptable abbreviation for certain minerals and rocks is obtained by leaving off the suffix "ite," as "calc" for calcite (cal is not acceptable because it is the standard abbreviation for calorie).

[1] I wish particularly to thank H. E. McKinstry and K. E. Lohman for reviewing the final lists and making several helpful suggestions.

2. Abbreviations, insofar as possible, should be recognizable contractions of the longer word and should be intelligible to other geologists.

3. Short words, such as ton, day and wad, should be spelled out.

4. Use of the same abbreviation for more than one word, obviously, should be avoided.

5. Letters, rather than chemical symbols, should be used for minerals. This is because many chemical symbols, such as FeS_2, may apply to more than one mineral.

6. Standard chemical symbols (capitalized) should always be used for the chemical elements. For example: Fe for iron, Au for gold.

7. Standard, generally accepted, abbreviations that are in common usage should always be used. Most of the larger dictionaries contain a list of standard abbreviations. These should be used in notetaking rather than thinking up new ones.

8. Lower case letters should be used, except when common usage or other rules specifically call for capital letters; i.e., "C" for Centigrade or for Cambrian.

9. The same abbreviation is used for both singular and plural, as "ls" for limestone and limestones.

10. In notetaking or in plotting data on maps, abbreviations should not be followed by a period, except when established usage or clarity requires it.

11. Usually, it is not necessary to have different abbreviations for nouns and adjectives. The context will tell which is intended. Example: "amyg" —amygdaloid or amygdaloidal; "bas"—basalt or basaltic.

12. Abbreviations, as well as symbols, used on maps and sections, should be included in the *Explanation*.

13. The letter symbols used on geologic maps to indicate age and name of rock formations or other rock units, insofar as is practicable, should follow the practice established by the U. S. Geological Survey. These usually consist of two or more letters—an initial capital letter for the name of the System and one or more lower case letters for the name of the rock unit; as "Qt" for Quaternary, lower terrace deposits; "Cpr" for Carboniferous Pottsville formation.

The standard usage of such contractions and symbols is illustrated on many of the published U.S.G.S. maps and, although there is much flexibility in practice, a general standardization for most terms is apparent.

14. All geologists in one survey party, or in the same organization, should use the same abbreviations. A list of standard abbreviations, as well as symbols, should be available in every mine office. When new or unusual abbreviations are used, the geologist should prepare an explanation to accompany his notes.

The rules outlined above have been followed as closely as possible in preparing the accompanying lists. An attempt has been made to use those contractions that are commonly used by geologists. Even so, conflicts are difficult to avoid. For example, "en" is used for enargite by mining geologists,

whereas "en" denotes enstatite to the petrographer; "gn" is used for both galena and gneiss. Where conflicts of this nature arise, the abbreviations used by field and mining geologists, for whom the standard lists are designed, have been chosen rather than the terms used by laboratory workers.

Where more than one abbreviation is in common usage for the same word; i.e., "qz", "qtz", "q" for quartz; "po", "por", "p" for porphyry, the preferred one is given first and is followed by the others. Because of the many conflicts, three letters have been adopted for colors.

ABBREVIATIONS

ROCK NAMES

Igneous rocks	
agglomerate	—agg
amygdaloid	—amyg
andesite	—and
anorthosite	—ano
aplite	—ap
basalt	—bas, bt
breccia	—bx, bc, br
diabase	—db
dacite	—da, dct
diorite	—di, dio
dolerite	—dole
dunite	—dun
gabbro	—gb, ga
granite	—gr
granodiorite	—grd, gd
hornblendite	—hbt
igneous	—ig
latite	—la
lava	—spell out
lamprophyre	—lamp
monzonite	—monz, moz
norite	—nor
obsidian	—obs
peridotite	—pd
pegmatite	—peg
phonolite	—phon
pillow lava	—pl
porphyry	—po, por, p
pumice	—pu
pyroxenite	—pyxt
quartz diorite	—qd
rhyolite	—rhy, ry
syenite	—sy
trap	—trp
trachyte	—tryt, tyt
tuff	—spell out, tu
sperulitic pillow lava	—spl

Sedimentary rocks	
argillite	—argl
arkose	—ark, ak
asphalt	—asph
banded iron formation	—bif
bitumen	—bit
conglomerate	—cg, cong, cgl
chert	—ch, ct
claystone	—cs
edgewise conglomerate	—ewcg
diatomite	—dtm
dolomite	—dol, dolo
graywacke	—gw
iron formation	—if
iron carbonate	—icarb, ic
ironstone	—is, ir
limestone	—ls
marl	—ml
mudstone	—ms
phosphate	—phos
quartzose iron formation	—qif
sedimentary	—sed
shale	—sh
shaly iron formation	—shyif
sandstone	—ss
siltstone	—slt, st
travertine	—trv

Metamorphic rocks	
anthracite	—anth
amphibolite	—amp, amph
ellipsoidal greenstone	—el gs
gneiss	—gns
greenstone	—gs
injection gneiss	—inj gns
magnetic slate	—mag sl
magnetic graywacke	—mag gw
marble	—mb
metamorphic	—meta
paragneiss	—pagns
orthogneiss	—orgns
phyllite	—phy
quartzite	—qte
schist	—sch
serpentine	—serp, sert
slate	—sl

General	
batholith	—bath
dike	—dk
lopolith	—lopo
mineral	—min, mnl
pluton	—plut
rock	—rk
specimen	—spec
stock	—spell out
stone	—stn
volcano	—vol

MINERAL AND METAL ABBREVIATIONS

Acanthite	—ac
Actinolite	—act
Adularia	—adu
Aguilarite	—agu
Aikinite	—ai
Alabandite	—abn
Albite	—ab
Algodonite	—alg
Allanite	—all
Alunite	—al
Altaite	—at
Amalgam	—amal
Amblygonite	—amb
Amphibole	—amp
Analcite	—anal
Andorite	—ad
Anglesite	—ang
Anhydrite	—anh
Animikite	—anm
Ankerite	—ank
Annabergite	—anna
Anorthite	—an
Antimony	—Sb
Antlerite	—ant
Apatite	—ap
Aragonite	—ara
Argentite	—arg
Argyrodite	—ay
Arsenopyrite	—asp
Arsenic	—As
Atacamite	—ata
Augite	—aug
Autunite	—aut
Azurite	—az
Baddeleyite	—bad
Barite	—ba
Bauxite	—baux
Becquerelite	—bec
Bementite	—bem
Biotite	—bio
Bismuth	—Bi
Bismuthinite	—bm
Bornite	—bn
Boulangerite	—bl
Bournonite	—bo
Brannerite	—bran
Braunite	—br
Bravoite	—bv
Breithauptite	—btp
Calamine	—cala
Calaverite	—ca, cl
Calcite	—calc
Canfieldite	—can
Carbon	—C, cbn, cb
Carbonate	—carb
Carnotite	—carn
Carrolite	—car
Cassiterite	—cs, ct, cx
Celestite	—cel
Cerargyrite	—cer
Cerrusite	—ce
Chalcocite	—cc
Chalcopyrite	—ccp
Chalcanthite	—chln
Chalcostibite	—cb
Chalmersite	—cm
Chert	—ch

Chloanthite	—cln, cl
Chlorite	—chl
Chromite	—cr
Chryscolla	—chrys
Cinnabar	—ci
Clausthalite	—ct
Clay	—spell out
Cobalt	—Co
Cobaltite	—cob
Coffinite	—cof
Coloradoite	—colo
Columbite	—colu
Coolgardite	—cool
Copper	—Cu
Corundum	—cor
Cosalite	—cos
Covellite	—cv
Crookesite	—ck
Cubanite	—cn
Cuprite	—cup
Cummingtonite	—cum
Cylindrite	—cy
Datolite	—dat
Descloizite	—des
Diaphorite	—diap
Dickite	—dick
Diopside	—diop
Dolomite	—dol, dolo
Domeykite	—dom
Dyscrasite	—dy
Epiboulangerite	—epib
Epidote	—ep
Emplectite	—emp
Enargite	—en
Enstatite	—ens
Erythrozincite	—eryz
Erythrite	—ery
Euxenite	—eux
Famatinite	—fm
Ferberite	—ferb
Fergusonite	—ferg
Feldspar	—fs, felds
Fluorite	—fl
Franckeite	—fc, fr
Franklinite	—fk
Freieslebenite	—freis
Galena	—gn
Gangue	—G
Garnet	—gar
Garnierite	—garn
Geocronite	—gc
Gersdorffite	—gf
Gibbsite	—gibb
Glaucodot	—gld
Goethite	—goe, gt
Gold	—Au
Goldfieldite	—glf
Goldschmidtite	—glm
Gossan	—gos
Graphite	—graph
Greenockite	—gk
Grunerite	—grun
Guanajuatite	—gt
Guitermanite	—gm
Gummite	—gum
Gypsum	—gyps
Halloysite	—hl
Hausmannite	—hs
Hematite	—hem
Hessite	—hs
Hewettite	—htt
Histrixite	—his
Hornblende	—hb
Huebnerite	—hub
Ilmenite	—il
Iron	—Fe
Itabirite	—ita
Jalpaite	—jl
Jamesonite	—jm
Jarosite	—jar
Jasper	—jas
Jasperoid	—jasp
Jordanite	—jd
Kalgoorlite	—klg
Kaolinite	—kaol
Keweenawite	—keew
Kermesite	—km
Klaprotholite	—kp
Kobellite	—ko
Krennerite	—kr
Kyanite	—ky
Labradorite	—lab
Laterite	—lt
Laumontite	—laum
Lead	—Pb
Lepidolite	—lep
Limonite	—lim, lm
Linnaeite	—ln
Livingstonite	—liv
Loellingite	—lo
Luzonite	—lz
Magnetite	—mag, mg
Malachite	—mala, mc
Manganite	—man, mng
Marcasite	—mar, ms
Matildite	—mt
Melonite	—melon

Meneghinite	—mene
Metacinnabarite	—mc
Miargyrite	—my
Millerite	—ml
Mineral	—min, mnl
Mohawkite	—mk
Molybdenite	—mo
Muscovite	—mus, mv
Nagyagite	—ng
Naumannite	—nm
Nephelite	—neph
Niccolite	—nc
Oligoclase	—ol
Olivine	—ov
Orthoclase	—or
Orpiment	—orp
Oxide	—ox
Patronite	—pat
Pearcite	—pc
Pentlandite	—pn, pent
Petzite	—pet
Phosphate	—phos
Pitchblende	—pthb
Plagionite	—pg
Platinum	—Pt
Plumbojarosite	—pbj
Polyargyrite	—plgy
Polybasite	—plb
Polydymite	—pm
Polyhalite	—pyh
Prehenite	—prh
Proustite	—pu, pru
Psilomelane	—psi
Pyrargyrite	—pr
Pyrite	—py
Pyroclore	—pyl
Pyrolusite	—pyrl
Pyromorphite	—pymp
Pyroxene	—px, pyx
Pyrrhotite	—po, pyrr
Quartz	—qz, qtz, q
Quicksilver	—Hg
Rammelsbergite	—rm
Realgar	—rl
Rhodochrosite	—rhod
Rhodonite	—rho
Rutile	—rt
Safflorite	—sf
Scheelite	—shee
Semseyite	—sems
Sericite	—ser, sr
Serpentine	—serp, sert
Siderite	—sid, sd
Siegenite	—sg
Silicate	—sil
Silver	—Ag
Sillmanite	—sill
Skutterudite	—sk
Smaltite	—sm
Smithite	—smtt
Smithsonite	—smith
Specularite	—specul
Sperrylite	—sperry
Sphalerite	—sp
Sphene	—sph
Stannite	—stan
Stephanite	—stp
Stibnite	—stib
Stilpnomelane	—stilp
Stromeyerite	—strom
Stutzite	—stut
Stylotypite	—sty
Sulfide	—sulf
Sulfur	—S
Sylvanite	—sv
Talc	—tc
Tantalite	—tan
Teallite	—teal
Telluride	—tell
Tellurium	—T
Temiskamite	—tk
Tennantite	—tn
Tenorite	—to
Tetrahedrite	—td
Tetradymite	—ty
Thomsonite	—thom
Thorite	—thor
Thucolite	—thuc
Tiemannite	—tie
Tin	—Sn
Titanite	—tit
Topaz	—tz
Torbernite	—torb
Tourmaline	—tl
Tremolite	—tm
Troilite	—tr
Tungsten	—W
Turquoise	—turq
Turgite	—turg
Tyuyamunite	—tyuy
Ullmannite	—ul
Umangite	—um
Uraninite	—uran
Uranophane	—urp
Vanadinite	—van
Vein quartz	—vqz
Vermiculite	—verm
Violarite	—vl
Voltzite	—vo

Warrenite	—wa	Zeolite	—zeo
Whitneyite	—wh	Zinc	—Zn
Willyamite	—wy	Zincite	—znc
Wolframite	—wf	Zinkenite	—zk
Wollastonite	—woll	Zippeite	—zip
Wulfenite	—wulf	Zircon	—zr
Wurtzite	—wurt	Zunyite	—zun

COLOR ABBREVIATIONS

black	blk, bk, bl	light	lgt, lt
blue	blu, bl, bu	orange	oran
bright	brt	purple	purp, pp
brown	brn, br, bn	red	red, rd
buff	buf, bf	steel	stl
chocolate	choc, cho	violet	vio
dark	drk	white	wht
drab	drb	yellow	yel, yw, yl
gray	gry, gy		
green	grn		

GRAIN AND TEXTURAL SIZES

Quantitative measurements are always desirable and should be recorded whenever possible. However, it is frequently difficult to be precise in geological field work and, therefore, qualitative terms are commonly used and are acceptable, particularly if the qualitative terms are given quantitative limits. In specific districts, after considerable experience and many measurements, it is possible to place quantitative limits on various expressions. For example, on the Colorado Plateau the U. S. Geological Survey uses the following terms for recording grain size during field mapping and logging core.

Wentworth Scale	*Millimeters*	*Abbreviations* *
Very fine	0.060–0.125	vf
Fine	0.125–0.210	fn
Medium fine	0.210–0.300	mfn
Medium	0.300–0.420	md
Medium coarse	0.420–0.600	mcse
Coarse	0.600–1.000	cse
Very coarse	1.000–2.000	vcse

* Abbreviations suggested by writer.

A good, practical field classification of sizes is the following:

Very fine grained	Grains not observed by naked eye—i.e., microcrystalline cherts	vfg
Fine grained	Less than 1 mm	fng
Medium grained	1–10 mm	mdg
Coarse grained	1–2 cm	csg
Very coarse grained	2 cm +	vcsg

Terms used by U.S.G.S. on Colorado Plateau:

pebbles	More than 4 mm + or 0.15 in	peb
granules	Less than 4 mm or 0.15 in and more than 2 mm or 0.08 in	gran
flakes	Paper thin, with two long dimensions	fks
seams	Less than 0.1 ft. thick	sms
films	Usually along lamination or cross-lamination planes	fms

DESCRIPTIVE AND STRUCTURAL TERMS

abundant	—abun	crushed	—crsd
altered	—alt	crystalline	—xln
alteration	—altn	crystalline, coarsely	—xln-c
angular	—ang	crystalline, finely	—xln-f
arenaceous	—aren	crystallized	—xld
argillaceous	—argill		
asphaltic	—asph	dark	—drk
		dense	—dns
band	—bnd	dike	—dk
banded	—bndd	discard	—dscd
banding	—bndg	disseminated	—dissm
bed	—bd	distributed	—distr
bedded	—bdd	dragfold	—dfld
bedded, thick	—tkbd		
bedded, thin	—tnbd	ellipsoidal	—elp
bedding	—bdg	enriched	—enr
below	—blw	extrusive	—extr
between	—btwn		
bentonitic	—bent	fault	—flt
bitumin	—bitum	favorable	—fav
bleb	—blb	ferruginous	—ferr
border	—bor	fine	—fn
bottom	—bot	fissle	—fss, fsl
break	—brk	fissure	—fiss, fisr
broken	—bkn	flakes	—fks
		flow cleavage	—flclvg
calcareous	—calc	fold	—fld
carbonaceous	—crb, carbon	foliation	—foli
cement	—cmt	foot wall	—F.W.
cherty	—chty	formation	—frm
cindery	—cndy	fossil	—foss
cleavage	—clvg	fracture	—frac
clear	—clr	fracture cleavage	—frac cleav
coarse	—cse	fragmental	—fragl
compact	—cpt	fragments	—frag
composition	—comp	friable	—fri
concentration	—conc		
concretion	—concr	glass	—gls
condense	—spell out	gouge	—go
condition	—cond	grade	—grad
conductivity	—conduct	gradational	—gradl
considerable	—consid	grain	—grn or spell out
cross-bedded	—x-bdd, xb	grained	—grn, grnd
crumpled	—crump	granular	—gran

ground	—gro
gneissosity	—gny
hanging wall	—H.W.
hard	—hd
heterogeneous	—hete
high grade	—h.g.
igneous	—ig
impregnated	—impreg
inclined	—incl
inclusions	—inclus
indurated	—indur
irregular	—irreg
interbedded	—intbd
intrusive	—intr
joint	—jo
jointing	—jotg
lamination	—lam
lean	—ln
lineation	—lin
location	—loc
low grade	—l.g.
magnetic	—mag
massive	—msv
material	—mat
medium	—med
metamorphic	—meta
mineral	—min, mnl
mineralized	—minz
mixed	—mxd
mottled	—mot
oölitic	—ool
opaque	—opq
outcrop	—otp, oc, otc
oxidized	—ox
pebble	—peb
phenocrysts	—phen
porphyry	—por
predominantly	—pred
proportion	—prop
rare	—spell out
refractory	—rfty
residue	—res
residual	—resd
rock	—rk
rocks	—rx
round	—rnd
sand	—sd
sandy	—sdy
scarce	—scar
schistosity	—schis
sediment	—sed
sheared	—shrd
sheeting	—shtg
siliceous	—silic
slickensides	—slick
slightly	—sly
soft	—sft
specimen	—spec
sticky	—stky
stock	—spell out
stone	—stn
straie	—spell out
strained	—spell out
streak	—strk
strike	—str
strong	—strg
structure	—struc
tarnished	—tnshd
thick	—tk
thick bedded	—tkbd
thin bedded	—tnbd
undulating	—und
unfavorable	—unfav
unoxidized	—unox
variable	—var
vein	—vn
veined	—vnd
veinlet	—vnlt
very	—vy
volcanic	—vol
wash	—spell out
weathered	—wth
weak	—wk
with	—+

ABBREVIATIONS FOR SURVEYING AND GENERAL SCIENCE

acre	—spell out
adit	—spell out
angle	—∠
atmosphere	—atm
atomic weight	—at wt
average	—avg
avoirdupois	—avdp
azimuth	—az
barometer	—bar
barrel	—bbl
base	—spell out
bench mark	—B.M.
back sight	—B.S.
boiling point	—bp
bushel	—bu

calorie	—cal
candle	—can
cent	—¢
center	—cent
center line	—℄
Centigrade	—C
centimeter	—cm
chemical	—chem
chemically pure	—cp
churn drill hole	—cdh
circular	—cir
concentrate	—conc
constant	—const
cord	—cd
cubic	—cu
cubic foot	—ft^3
cubic centimeter	cc, cm^3
day	—spell out
degree	—deg or °
diamond drill hole	—ddh
diameter	—diam
outside diam	—o.d.
inside diam	—i.d.
dozen	—doz
drill hole	—dh
elevation	—elev
equation	—eq
external	—ext
Fahrenheit	—F
foot	—ft
fore sight	—F.S.
freezing point	—fp
frequency	—freq
gallon	—gal
gram	—g
grain	—grn or spell out
greater than	—>
height of instrument	—H.I.
high pressure	—h-p
horsepower	—hp
hour	—hr
inch	—in
internal	—int
interval	—invl
kilogram	—kg
kilometer	—km
kilowatt	—kw
latitude	—lat
less than	—<
liquid	—liq
liter	—spell out
longitude	—long
low pressure	—l-p
manhole	—mh
mass	—spell out
maximum	—max
melting point	—mp
meter	—m
mile	—mi
millimeter	—mm
minimum	—min
minute (angular measurement)	—min or ′
minute (time)	—spell out
molecular weight	—mol wt
month	—spell out
monument	—mon
nail	—na
ounce	—oz
parallel	—//
parts per million	—ppm
penny	—d
pennyweight	—dwt
point of intersection	—P.I.
point of tangency	—P.T.
point	—pt
pound	—lb
railway	—ry
railroad	—rr
range	—R
raise	—rz
road	—rd
section	—sect
second (time)	—sec
second (angular measurement)	—// sec
specific gravity	—sp gr
square	—sq
square foot	—sq ft or ft^2
standard	—std
stadia station	—⊡
stake	—stk
tack	—spell out
temperature	—temp
ton	—spell out
township	—twp
turning point	—⊙ or T.P.

tunnel	—tun	winze	—wz
triangulation station	—△	weight	—wt
traverse point	—⊙ or tp	yard	—yd
vertical	—vert or ⊥	year	—yr

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DISCUSSIONS

CONCENTRATION OF URANIUM BY CARBON COMPOUNDS

Sir: I shall not involve J. W. Gruner in the discussion on Witwatersrand uranium that, understandably, he wishes to eschew; yet it seems relevant to mention that it was he himself who first referred to Rand thucholite in the recent correspondence in ECONOMIC GEOLOGY (1). Although I am impressed by the willingness with which he now accepts Ramdohr's confirmation of my conclusions on the relative ages of the South African uraninite and hydrocarbon, "the only thing on which the two authors agree," I am surprised that he should characterize as "objective" a work which is founded on the assumption that uraninite, a mineral soluble in most chemical environments, can persist with a notional detrital form completely unchanged throughout the geological vicissitudes of two milliard years, while in the same ores gold, the paragon of chemical stability, is admitted to be so dissolved and redistributed that not a vestige of its detrital form remains. But these are matters that have been dealt with elsewhere (2).

It was Gruner also who first made reference to this correspondence to the uranium ores of Temple Mountain in the San Raphael Swell, my brief study of which is now said to be "unfortunate" in that the deposit is unrepresentative. No more representative deposit was mentioned by him. His deduction that carbonaceous matter of organic origin is an excellent collector of uranium is one that has long been widely accepted—as long ago as 1944 in a classified report written after a tour of the Colorado Plateau I suggested that uranium might be recovered commercially from leach liquors by passing them through peat!—and there is general agreement that a great many of the Plateau deposits have been formed in this way. This conclusion holds irrespective of whether the mineralized fluids were of meteoric or of hydrothermal origin. In the Carboniferous and Triassic sandstones of Britain, far removed from evident hydrothermal mineralization, isolated fragments of wood trash are in places mineralized with uraninite and sulphides. But the hydrocarbon-uraninite aggregate known as thucholite found in hydrothermal polymetallic veins such as Nicholson in Canada or Laxey in Britain clearly cannot have such an origin. It is evident from a recent publication of Isachsen (3) of U.S.A.E.C., whose conclusions agree with my own, that not all the "several institutions that have spent much time investigating the Temple Mountain 'asphaltite' find a weight of evidence pointing towards an origin and composition directly connected with wood extracts."

My reply to Gruner was not a "criticism" but a challenge—to "name some noteworthy concentrations of primary uranium mineralization situated within an oil and gas province where the ore is *not* accompanied by hydrocarbon."

An oil and gas province is a region where oil and gas are *known* to exist—not one in which they *may* exist or *may have* existed. Many cases are now on record where thucholite occurs in mines in which a noteworthy concentration of hydrocarbon gases has been found. Can Gruner, or anyone else, point to a uranium mine anywhere in which hydrocarbon gases are common in the mine air or in the adjacent country rock and where the uraninite is not partly 'thucholitized'? Until this is done, the deduction that the 'carbon' which so often *replaces* uraninite is a natural, radioactivity-induced, polymerization or condensation of fluid hydrocarbons or oxyhydrocarbons would seem to rest on a surer foundation than most hypotheses in economic geology.

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4th July, 1956

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URANIFEROUS MAGNETITE–HEMATITE DEPOSIT AT THE PRINCE MINE, NEW MEXICO

Sir: A recent article by Walker and Osterwald [1] contains some examples of dubious reasoning in the application of chemistry to ore deposition. In pointing out these examples, I am not implying any criticism of the article as a whole, nor am I suggesting that the logical sins here are worse than in several other papers. My intention is only to express an opinion that theoretical discussions in economic geology could be made clearer and more meaningful if such sins were avoided, and for this purpose Walker and Osterwald's paper is a convenient starting point.

(1) "Because the melting points of iron and uranium are relatively close (respectively, 1,535 and 1,150° C), the iron and uranium at the Prince mine originally may have been mobilized and concentrated more or less simultaneously." To back up this extraordinary statement the authors refer to a paper by Sullivan.[2] Sullivan's hypothesis deserves oblivion rather than discussion, but something should be said about it if future writers are going to quote it with a straight face. Sullivan's argument (which has been criticized before, albeit much too gently, by Wyman [3]) is essentially this: melting points of metals show a rough correspondence with distribution of metals in ores;

[1] THIS JOURNAL, v. 51, May 1956, p. 213–222.
[2] THIS JOURNAL, v. 49, p. 555–574.
[3] THIS JOURNAL, v. 49, p. 900–904.

therefore differences in melting point *cause* the observed distribution. One could argue with equal cogency that the singing of birds coincides with the rising of the sun, and that *therefore* the singing *causes* the sun to appear. Sullivan perhaps has a right to publish such nonsense, but there seems no need to perpetuate it.

Parenthetically, Sullivan's reasoning could equally well be applied to properties of metals other than melting points. Magnetic susceptibilities, for example, show a fair correspondence with distribution of metals in depth and temperature zones. Someone is missing a golden opportunity to immortalize himself by proposing a hydromagnetic theory of ore deposition.

(2) Walker and Osterwald continue: "Conceivably both elements were primary constituents of the monzonite magma and were extracted at about the same time from the crystallizing melt. On the other hand, they may have been extracted from the invaded rocks, either through assimilation of wall rock or diffusion of these substances into the magma. . . ." One wonders where else they might have come from—maybe out of the air? In my opinion it serves no useful purpose to enumerate possibilities when the enumerating has already been done ad nauseam in standard textbooks. The situation is different if one wants to *discuss* the possibilities, to show reasons why one is better than the others—but Walker and Osterwald merely name them.

(3) "Although finite temperature and pressure conditions cannot be established" (maybe it is unfair to quibble over a single word, but this clause means to me that infinite temperature and pressure cannot be excluded) ". . . the temperature is thought to have been *relatively* low because: (1) The contact-metamorphic aureole enclosing the ore body is *relatively* thin, and (2) the aureole is composed, in part, of *relatively* low-temperature contact-metamorphic minerals rather than high-temperature contact-metamorphic minerals . . ." (italics mine). One would enquire first, *relative* to what? The facts here, it seems to me, are simply these: Temperatures in contact-metamorphic zones have a range from about 100 to about 700° C; the effect of pressure is less important than that of temperature; ordinarily temperatures cannot be precisely determined, but the nature of the minerals and the width of the metamorphic zone give some indication of temperature. Why not accept these as generally known, and reduce the verbiage accordingly? Something like this: The temperature of ore deposition, as judged by the associated minerals and the thickness of the metamorphic aureole, was in the lower part of the contact-metamorphic range.

(4) "The physical and mineralogic character of the aureole may be more largely dependent, however, on the composition and volume of the silicating solution, the permeability of the country rock, and the relative pressure gradient at time of mineralization. . . ." Also, presumably, on the phase of the moon. This is another example of an exhaustive listing of pretty obvious alternatives, with no attempt to choose among them.

(5) In reference to an article by Shand:[4] "Such solutions from crystallizing magmas are postulated to be relatively enriched" (again, relative to what?) "in sodium and potassium ions and thus have an alkaline reaction."

[4] THIS JOURNAL, v. 42, p. 634–636.

Shand's original statement is this: "If the residual liquid is alkaline, as any solution must be which contains strong cations and weak silica-alumina anions. . . ." Shand is using "alkaline" in the strict chemical sense, referring to an excess of OH^-; Walker and Osterwald pervert it to the all-too-common geologic usage of "rich in sodium and potassium." The quotation continues: "The intrusive rocks near the Prince mine are rich in feldspar and hence, were probably formed from a mildly alkaline magma; residual solutions were probably also alkaline." So far the usage is at least consistent; "alkaline" refers to the alkali metal ions. Then: "Shand believes the solutions contain a hydrosol of ferrous hydroxide, kept in suspension by the alkalies. His belief is supported by the fact that ferrous hydroxide is insoluble in alkaline solutions." This heaps confusion on confusion. In the last sentence "alkaline" must refer to excess of OH^-, for surely Na^+ and K^+ in themselves have nothing to do with the insolubility of ferrous hydroxide. The meaning in the next-to-last sentence is obscure; Shand certainly makes no claim that the alkali metal ions keep the hydrosol in suspension (they would be expected to have the opposite effect), yet one doesn't usually refer to excess OH^- by the plural "alkalies." Furthermore, the elementary fact that ferrous hydroxide is insoluble cannot possibly be construed as supporting the notion that the hydrosol is kept in suspension by the alkalies. And finally, it seems to me a great disservice to Shand to describe the hydrosol idea as an article of faith ("Shand believes . . ."), when Shand very carefully proposes it as a promising hypothesis regarding which "further experimental study . . . is highly desirable."

(6) "The coagulation of such a hydrosol would be aided by $MgSO_4$ or $K_2Cr_2O_7$ as electrolytes in the solution." To bolster this statement, reference is made to a physical chemistry text. This particular book I do not have at hand, but it would be extraordinary if such a text should single out these two salts as special coagulants for ferrous hydroxide. In the first place, $K_2Cr_2O_7$ cannot exist in alkaline solution (chemically alkaline), and in the second place it would be immediately reduced by ferrous hydroxide. But these are minor points; my chief grievance here is that any other salt containing a divalent ion would be equally effective in coagulating the hydrosol, so that to emphasize these two gives a very misleading impression.

Again may I disclaim any intention of picking on the authors of this particular article as worse offenders than many others. Their chemical indiscretions have served me only as convenient examples, which I think should be pointed out in the interest of making chemical discussions of ore deposits more rigorous and more consistent with contemporary chemistry.

KONRAD B. KRAUSKOPF

STANFORD UNIVERSITY,
June 1, 1956

REVIEWS

Contribution à l'Etude des Minéraux Secondaires d'Uranium Français. By JEAN CHERVET and GEORGES BRANCHE. Pp. 235; pls. 9; figs. 35. Sciences de la Terre, No. 1–2, Tome III, Université de Nancy, 1955.

At first glance, the reader's attention is captured by the exceptional quality of the photographs, particularly by the sharpness and general attraction of the twenty-four colored ones, which illustrate bright microscopic crystals of secondary uranium.

The increasing importance of uranium minerals has led to the development of a new field of interest which, although primarily of great academic importance, has now found many applications in the study of uranium ores.

Ten years of research are condensed into the present work, in which the authors intend to give as accurate a description as possible of secondary minerals of the uranium family found in France and elsewhere in the French Union. They also hope to synthesize the work done in other countries concerning the mineralogy of these secondary minerals.

In the first part, an historic account of the study of most of the twenty-seven known secondary minerals points out the early interest of mineralogists and chemists in these colorful minerals, and the still increasing interest of modern scientists.

The description that follows is based on material obtained mainly in France and also in North Africa, Madagascar, The Belgian Congo, etc., and for that reason a certain provinciality would have appeared if a good comparison had not been drawn up between the prototypes and the varieties found elsewhere.

The minerals are grouped after Lacroix's classification under the following titles: Crystallography, Forms, Cellular structure, Facies, Physical-, Chemical-, Optical properties, Occurrences and Associations.

Uncertain mineralogical kinds and new ones recently found are mentioned. A useful list of known kinds with their synonyms and an up-to-date bibliography constitute the last part of the book.

This work shows the way to this new field of investigation, and we hope that it will be of great help to specialists of uranium mineralogy.

JEAN BÉRARD

FORT CHIMO,
Aug. 13, 1956

Handbuch der Mikroskopie in der Technik. By HUGO FREUND. Band II, Teil 2, pp. 654; figs. 524. Umschau Verlag, Frankfurt am Main, 1956. Price, DM. 96.

This volume is part of a large work in progress under the direction of the author. Volume I, in two parts, has already appeared. Part 1 deals with the microscope with transmitted light, and Part 2, with the microscope with reflected light. Volume II is entitled *Mikroskopie der Bodenschätze*. Part 1 of Volume II, which preceded this volume, dealt with the microscopy of coal, coke and brown coal. This volume, Part 2, is entitled "Mikoskopie der Erze, Aufbereitungsprodukte und

Hüttenschlacken." The third part of this volume, to follow, will deal with microscopy of petroleum and salts. Six more volumes are to follow.

This book is made up of nine sections by as many authors. They are: development of the ore microscope, by O. Friedrich; the reflecting microscope in the investigation of ore deposits, by Paul Ramdohr; microscopy of iron ores, manganese, titanium and chromium, by O. Friedrich; precious metals and nonferrous metals, by G. Rehmald; various microscopes and their uses, by H. Ehrenberg; goniograph, by P. Siedler; blast furnace slags, by K. Obenauer; metalliferous slags, by W. Faber; rock dusts etc., by M. Zandmehr. Each section is followed by an appropriate bibliography.

All of the sections are beautifully illustrated. This is particularly true of Paul Ramdohr's article, which covers the ore types of each class of deposit according to the Schneiderhöhn classification.

The opening section on the development of the ore microscope carries a fairly complete bibliography of each author who has made contributions to the subject.

This volume is of particular interest to economic geologists since it deals with the use of the ore microscope as applied to various kinds of ores, mill products and slags, the techniques, the textures and their interpretation. It will serve as a valuable reference to all users of the microscope, and as a supplementary reference to text books on mineralography.

Structural Geology. By L. U. DE SITTER. Pp. 552; figs. 309; tbls. 15. McGraw-Hill Book Co., New York, 1956. Price, $11.00.

All geologists will welcome a book on structural geology by so distinguished a geologist as the Professor of Geology at the University of Leiden. His extensive field experience and his scholarly writings have already made him widely known throughout the world. He is well qualified to establish the link between the theory and practice of orogenesis.

The author states in his preface that this book is intended for the trained geologist rather than the layman or the first-year student. He says it presupposes familiarity with the elements of the subject and its terminology.

The book is divided into three parts. Part I, Theoretical Structural Geology, takes up the physical properties of rocks, rock strain, experimental tectonics, rock behavior, fracturing and distortion, and cleavage and distortion. Part II is called Comparative Structural Geology. It takes up faults, joints, folding cleavage, diapiric and collapse structures, gravitational gliding, syntectonic and post-tectonic sediments, contorted beds, and microstructures. Part III, entitled Geotectonics, deals with fundamental concepts, magmatic phases, the Mediterranean and American mountain chains, island arcs, shields, basin structures, blocks, theories of orogenics, and of the cause of orogeny, and synthesis.

The coverage is broad. It starts with simple features and leads up to more complex ones as exhibited by the largest units and delves into their origins. The author states that the book is primarily concerned with systematizing our detailed knowledge so that we can distinguish genetic relationships. This phase particularly shows the results of the author's broad field experience and his ability to theorize from the field results, rather than not seeing the forest for the trees. With one of his statements we will all agree, namely, he believes what he sees more than what he reads.

The book is very nicely illustrated and well written and printed. It is a welcome addition to advanced structural geology and is bound to become a "must" to all advanced students of structural geology.

Geophysical Case Histories, Volume II—1956. Edited by PAUL L. LYONS. Pp. 676; illus. Society of Exploration Geophysicists, Tulsa, Okla., 1956.

This Volume II is made up of 53 papers by 75 authors, assembled from papers published by the Society of Exploration Geophysicists and the American Association of Petroleum Geologists, and additional material. This volume supplements Volume I which was published eight years ago; it is a continuation of that volume. However, in this volume the case histories have been grouped by type of trap instead of by geologic province. Also, this volume contains, in addition to the case histories of many outstanding fields, those of many major pools.

The preface states that the reader will note "the astonishing rise in the employment of telluric prospecting" which is a geophysical method not developed intensively in the United States.

There are seven sections. The first is general and historical papers to the number of six. Section 2, Salt Dome Histories, consists of six papers, mainly dealing with Louisiana. Section 3 has six papers, mainly on Texas and Alberta, dealing with reef histories. Section 4, the largest, is made up of twenty-four papers on Anticline Histories, of which five are foreign. Section 5, on Stratigraphic, contains three papers. Section 6, on Mining Case Histories, deals with Japan and Arizona. Section 7, the last, is called New Uses Case Histories, and has five papers dealing with Italy, Niger, Pennsylvania and Massachusetts.

Each paper is carefully done and well illustrated. The volume presents a mass of data in oil fields, and will prove a handy reference to all petroleum geologists and students of the subject.

Geology and Ourselves. By F. H. EDMUNDS. Pp. 254; pls. 12. Philosophical Library, New York, 1956. Price, $10.00.

The author dips into his wide and varied experience of the economic applications of geology to show in this book the importance of geology in our every day lives. It is not intended as a text book, but entirely for the layman. His illustrative material is drawn from his experience in Great Britain.

After eight pages of the history of geology, the author devotes three short chapters to the broad principles of geology, covering physical geology, ore minerals, rocks and fossils, and the history of the earth. In succeeding chapters, the author takes up geochemistry, bored wells, water supply, building materials, civil and structural engineering, coal and coal mining, ores, prospecting and mining, oil and gas, geology and agriculture, "Planning, Mining Subsidences, and Other Matters," and geology for the amateur. The book is illustrated with many drawings and photographs.

The book is very clearly written in simple language with a minimum use of geologic terms. The subjects, naturally, are treated quite lightly, for example, five pages for geophysics, and four pages for ores. That was the author's purpose. In this, he has succeeded well and has given an interesting and clearly written account of geology and some of the work a geologist does. The price of the book, however, is out of proportion to its simplicity and brevity.

Middleton & Chadwick's A Treatise on Surveying, Sixth Edition. Edited by W. FISHER CASSIE. Volume One, pp. 381, figs. 197; Volume Two, pp. 438, figs. 162. Philosophical Library, New York, 1956. Price, $20.00 the set.

A Treatise on Surveying has been a standard work through five editions. This sixth edition has been recast and rewritten. An expert in his field has written

each chapter (names not given). The subjects covered in Volume One are chain surveying, levelling and contouring, traverse surveying, curve ranging, tacheometric surveying, the plane table, and drawing office practice. Volume Two deals with survey adjustments, base lines, triangulation, levelling, traversing, field astronomy, hydrographic surveying, photogrammetry, reconnaissance and engineering surveys, cadastral surveying, reproduction of maps, and figure of the earth. New techniques in surveying are also included, such as echo sounding and location of aircraft in air surveying.

The revised edition should continue the good reputation of its predecessor volumes.

BOOKS RECEIVED

KURT SERVOS

La val di peio e la catena Vioz-Cevedale. CIRO ANDREATTA. Pp. 336; figs. 107; pls. 5. Societa Tipografica Mareggiani, Bologna, 1954. *Geologic map, 1:25000.*

Bureau of Mineral Resources, Geology and Geophysics, Melbourne, 1956. The Australian Mineral Industry, Vol. 8; No. 4. J. A. DUNN. Pp. 95; tbls. 9. Price 3/–. *Development and treatment have been the outstanding events in the Australian mineral industry during 1955 and 1956. Total value in 1955 was £195 million.*

Belgrade Technical School, Geological Faculty, Technical School, Belgrade, 1953–54. Pp. 353. *The 30 diverse papers are in Russian.*

British Columbia Department of Mines—Victoria, 1956. Preliminary Map Granduc Area. W. R. BACON. *One map sheet. Scale, 1:63,360.*

Geological Survey Department, Nicosia, Cyprus, 1956. Annual Report of the Geological Survey Department for the year 1955. F. T. INGHAM. Pp. 40. Price, 100 mils. *The value of mineral exports during 1954 and 1955 was more than £20 million, constituting more than half the value of all exports. Besides copper the island yields asbestos, chrome ore, gold and silver, gypsum, clay, and building stone.*

This is Israel. THEODORE HUEBENER AND C. H. VOSS. Philosophical Library, New York, 1956. Pp. 166. Price, $3.75. *Historical and cultural background of Palestine and the Hebrews; development of Judaism and Christianity, Saracen invasions, Crusades, Turkish Rules and British Mandate; establishment of Israel and its political problems.*

Department of Mines and Natural Resources, Winnipeg, 1956. Publ. 55–1. Geology of the Booster Lake Area Lac du Bonnet Mining Division. J. F. DAVIES. Pp. 15; fig. 1. *Geologic map, 1:12,000.*

École National Superieure de Geologie, Nancy, 1955. Pp. 312; pls. 12. *This monograph entitled "The exchange of constituents during the genesis of acid and basic rocks" presents the papers and discussions of twenty-eight petrologists, an international representation, who met in Nancy to consider the origin of "igenous" and metamorphic rocks. In French.*

Commissariat a L'Energie Atomique, Nancy, 1955. GEORGES BIGOTTE. Pp. 243; figs. 45; pls. 21.

Department of Mines and Technical Surveys, Ottawa, 1956. Publications of the Dominion Observatory. W. E. T. SMITH. Pp. 339–360. Price, 25 cts.

Consejo Superior de Investigaciones Cientificas, Barcelona, 1955. Publicaciones del Departamento de Cristalografia y Mineralogia. J. L. AMOROS *et al.* Pp. 79–158.

Uganda Geological Survey—Entebbe, 1956. The Geology of Part of South-East Uganda with special reference to the alkaline complexes. K. A. DAVIES. Pp. 76. Price, 20/–.

Illinois State Geological Survey, Urbana. Guide for Beginning Fossil Hunters. C. W. COLLINSON. Pp. 34; pls. 11. Price, 25 cts.

Minerals and the Microscope. M. K. WELLS. Macmillan Company, New York, 1956. Pp. 148; figs. 23; pls. 13. Price, $3.00. *This little book is not a theoretical text on crystal optics, but rather an elementary guidebook to serve as an introduction to petrographic methods. The principal topics are the construction and use of the petrographic microscope, the principles of crystal optics, the behavior of minerals in polarized and in convergent light, and the nature of the rock-forming minerals.*

Utah Geological and Mineralogical Survey, Salt Lake City, 1956. Clays of Utah County, Utah. E. P. HYATT. Pp. 83; fig. 22; tbls. 4. Price, $2.00.

Australia Bureau of Mineral Resources, Geology and Geophysics—Canberra, 1954–56.

Bull. 21. The cape range structure of Western Australia. M. A. CONDON *et al.* Pp. 82; pls. 18. *The structure is in anticline, with a closure of 1200 feet, in Cenozoic limestone.*

Bull. 26. The geology and mica-fields of the Harts Range, Central Australia. G. F. JOKLIK. Pp. 226; pls. 30; figs. 59; tbls. 35.

Bull. 28. Beach-sand heavy-mineral deposits of eastern Australia. D. E. GARDNER. Pp. 103; figs. 4; pls. 27; tbls. 34. *A large part of the world's zircon and rutile supply has come from deposits along Australia's east coast.*

Bull. 29. Permian pelecypods from the Carnarvon Basin, Western Australia. J. M. DICKINS. Pp. 42; pls. 6. *Two new genera and seven new species are described.*

Rept. 12. Stratigraphy and micropalaeontology of the marine Tertiary rocks between Adelaide and Aldings, South Australia. I. CRESPIN. Pp. 65; pls. 7; tbls. 2.

Rept. 25. Papers on Tertiary micropalaeontology. I. CRESPIN *et al.* Pp. 77.

British Guiana Geological Survey—Georgetown, 1956.

Bull. 29. The geology of the Issineru-Enachu district, Mazaruni River, British Guiana. E. R. POLLARD. Pp. 63; figs. 4. Price, $1.00. *Diamonds and gold comprise the principal economic mineral resources. Geologic map, 1:125,000.* **Report on the Geological Survey Department for the Year 1954.** Pp. 106. Price, $1.00.

California Division of Mines—San Francisco, 1956.

Calif. Jour. Mines and Geology, v. 52, no. 2. Pp. 107–227; pl. 1. Price, $1.00. *Many aspects of clay minerals are treated in eleven papers.* **Vol. 52, no. 3.** Pp. 231–291; figs. 19; pls. 7. Price, $1.00. *Gold ore shoots in Sierra County are characterized by extreme richness, erratic distribution and small size. The history of borax production in U. S. is reviewed on the occasion of the 100th Anniversary of its detection in California.*

Sp. Rep. 45. Exploratory wells drilled outside of oil and gas fields in California to December 31, 1953. C. W. JENNINGS and E. W. HART. Pp. 104; figs. 2; pl. 1. Price, $1.50.

Illinois State Geological Survey—Urbana, 1956.

Circ. 216. Germanium in fly ash and its spectrochemical determination. J. S. MACHIN and JUANITA WITTERS. Pp. 13; tbls. 6.

Circ. 217. Classification of the Pennsylvanian rocks of Illinois as of 1956. H. R. WANLESS. Pp. 14.

Rept. of Invest. 194. Groundwater geology of Lee and Whiteside Counties, Illinois. J. W. FOSTER. Pp. 67; figs. 9.

Rept. of Invest. 195. Preliminary report on Portland cement materials in Illinois. J. E. LAMAR *et al.* Pp. 34; figs. 3; tbls. 3.

Rept. of Invest. 196. Groundwater geology of White County, Illinois. W. A. PRYOR. Pp. 50; figs. 21; pls. 4.

Geological Survey of Japan—Hisamoto-cho, Kawasaki-shi, 1956.

The geological survey of Japan its history, organization and work. Editors; T. MURAKOSHI, K. HASHIMOTO. Pp. 266; figs. 32; tbls. 43. *This volume, commemorating the 70th Anniversary of the Geological Survey of Japan, presents an English summary of geology and mineral resources. Production of Au, Ag, Cu, Zu, Pb Bi and Cd are nearly sufficient to the domestic demand; iron and ferro-alloy metals are gravely scarce.*

Geological map of Japan. One sheet. *Scale, 1:2,000,000.*

Geological map of Nagoya. One sheet. *Scale, 1:200,000.*

Geological map of Toyohashi. One sheet. *Scale, 1:200,000.*

Rept. 168. Natural gas in the vicinity of Kobayashi, Southern Kyushu. KAZUYOSHI IDA, KOJI MOTOJIMA and NOBORU YASUKUNI. Pp. 46; figs. 26; tbls. 8. *Gas occurs in sediments of an ancient lake. Total gas reserve is estimated at less than 10 million cubic meters.*

Rept. No. 6. Liberal Arts Faculty Shizuoka University. Natural science. TOSHIHARU IKUTA *et al.* Pp. 35.

Rept. No. 7. Liberal Arts Faculty Shizuoka University. Natural science. ITIZO KAWAI *et al.* Pp. 68.

Rept. No. 8. Liberal Arts Faculty Shizuoka University. Natural Science. ITIZO KAWAI *et al.* Pp. 58; pl. 1.

Kansas State Geological Survey—Lawrence, 1956.

Bull. 117. Geology and ground-water resources of Rawlins County, Kansas. K. L. WALTERS. Pp. 100; figs. 12; tbls. 7; pls. 6.

Bull. 119, Part 3. Chemical composition of eastern Kansas limestones. R. T. RUNNELS and J. A. SCHLEICHER. Pp. 81–103; fig. 1; tbls. 31.

Bull. 119, Part 4. The mineral industry in Kansas 1950 to 1954. W. H. SCHOEWE. Pp. 109–174; figs. 2; tbls. 48. *The value of mineral production was more than $2 billion.*

Boletin Del Centro de Documentacion Cientifica y Tecnica de Mexico. Vol. 5; no. 3. Pp. 385–429. **Vol. 5; no. 4.** Pp. 587–627.

North Dakota Geological Survey—Grand Forks, 1955.

Rept. of Invest. 23. General Geology of Uranium in southwestern North Dakota. J. R. BERGSTROM. One sheet. *Field evidence indicates that uranium in lignite has an epigenetic origin.*

Ohio Department of Industrial Relations—Columbus, 1955.

Annual Coal and non-metallic mineral report. D. W. ALLOWAY. Pp. 175; tbls. 41. *Coal production for Ohio in 1955 was more than 37 million tons.*

Ohio Department of Natural Resources—Columbus, 1955–1956.

Mineral Industry Map of Ohio. R. W. SMITH. *One sheet. Scale, 1:5,000,000.*
Landform Map of Ohio. J. A. BIER. *One sheet. Scale, 1:1,250,000.*

Rept. Invest. No. 28. The economic geology of Crawford, Marion, Morrow and Wyandot Counties. J. F. HALL and R. L. ALKIRE. Pp. 43; figs. 11; tbls. 9. Price, 97 cts.

Quebec Department of Mines—Quebec, 1956.

Geol. Rept. 65. Montauban-les-mines area. J. R. SMITH. Pp. 39. *Mineralization is primarily lead-zinc. Geologic map, 1:12,000.*
Geol. Rept. 71. North Half of Obalski Township. R. B. GRAHAM. Pp. 44; tbl. 1. *Mineralization includes magnetite-ilmenite, base-metal sulphides, and gold. Two geologic maps, 1:12,000.*

Geological Society of South Africa—Johannesburg, 1955.

Transactions and Proceedings. Pp. 387; figs. 74; tbls. 25; pls. 46. *Nine diverse papers discuss geomorphology, petrology, stratigraphy, and economic geology. A monographic study of the occurrence and origin of gold and radioactive minerals in the Witwatersrand System reports that uraninite is distributed throughout conglomerates as deterital grains and that detrital uraninite is prerequisite for the formation of secondary uraninite and for thucholite. Gold is chiefly authigenic. The conclusion of a thorough investigation is that the gold and uraniferous constituents have an origin best explained by the modified placer theory.*

Alex. L. du Toit Memorial Lectures. No. 4. Some Aspects of the Geomorphology of Central and Southern Africa. F. DIXEY. Pp. 58; figs. 12; tbls. 3.

Tanganyika Geological Survey Department—Dar es Salaam, 1956.

Vol. 4, 1954. Records of the Geological Survey of Tanganyika. Pp. 118; Price, 7/50. *Besides preliminary reports this volume includes findings of completed surveys.*

U. S. Geological Survey—Washington D. C., 1955.

Prof. Paper 278. Geology and Ore Deposits of the Bagdad Area, Yavapai County, Arizona. C. A. ANDERSON, E. A. SCHOLZ, and J. D. STROBELL, JR. Pp. 103; pls. 6; figs. 33; tbls. 10. *Au, Ag, Cu, Pb, and Zn have been produced at different times (with a total value of more than $31 million) but now the most important metals are copper and wolfram.*

Prof. Paper 300. Contributions to the Geology of Uranium and Thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955. L. R. PAGE, H. E. STOCKING, and H. B. SMITH. Pp. 739. *The 89 papers cover nearly every aspect of uranium geology.*

Bull. 1016. The Wishbone Hill district, Matanuska coal field, Alaska. F. F. BARNES and T. G. PAYNE. Pp. 88; pls. 20; fig. 1; tbls. 4. Price, $2.50. *Reserves are estimated at 102 million tons in this district that has been producing coal continually since 1916.*

Bull. 1023. Bentonite deposits in marine Cretaceous formations, Hardin district, Montana and Wyoming. M. M. KNECHTEL and S. H. PATTERSON. Pp.

116; pls. 2; figs. 12; tbl. 1. *Minable reserves are estimated at 110 million short tons of montmorillonitic clay. Geologic map, 1:62,500.*

Bull. 1024-D. Magnetite deposits at Tuxedni Bay, Alaska. ARTHUR GRANTZ. Pp. 95–106; figs. 4; tbls. 2. Price, 15 cts. *The deposit has a pyrometasomatic origin and is 30 to 35 feet thick where exposed.*

Bull. 1024-E. Pyrite deposits at Horseshoe Bay, Latouche Island, Alaska. F. A. STEJER. Pp. 107–122; pl. 1; figs. 4. Price, 45 cts. *The deposits are a possible economic source of sulfur.*

Bull. 1027-J. Geology of the Stanford-Hobson area, central Montana. J. D. VINE. Pp. 405–470; pls. 3; figs. 10; tbls. 6. Price, $1.25. *Materials of possible economic importance include oil and gas, coal, gypsum, bentonite and gravel.*

Bull. 1027-M. Reconnaissance geology of western Mineral County, Montana. R. E. WALLACE and J. W. HOSTERMAN. Pp. 575–612; pls. 4; figs. 3. Price, $1.25. *The geology and mineralogy are similar to the Coeur d'Alene district but, in comparison, production is extremely small. Much more exploration is warranted.*

Bull. 1027-O. Thorium and rare-earth minerals in Powderhorn district, Gunnison County, Colorado. J. C. OLSON and S. R. WALLACE. Pp. 693–723; pls. 2; figs. 1; tbls. 4. Price, 60 cts. *The Th deposits are veins and mineralized shear zones. Rare-earths are borne in minerals that occur in carbonate veins.*

Bull. 1042-A. Geology of the Johnson Creek quadrangle, Caribou County, Idaho. R. A. GULBRANDSEN, K.P. MCLAUGHLIN, F. S. HONKALA, and S. E. CLABAUGH. Pp. 23; pls. 2; fig. 1. Price, 75 cts. *Phosphate rock is the only important mineral resource.*

Bull. 1042-B. Airborne and ground reconnaissance of part of the syenite complex near Wausau, Wisconsin. R. C. VICKERS. Pp. 25–44; figs. 5. Price, 15 cts. *Reconnaissance disclosed many thorium-bearing minerals.*

Bull. 1048-A.—Geophysical Abstracts 164 January–March 1956. M. C. RABBITT *et al.* Pp. 92. Price, 25 cts.

Water-Sup. Pap. 1328. Ground-water resources of the Hopkinsville quadrangle, Kentucky. E. H. WALKER. Pp. 98; pls. 4; figs. 20; tbls. 7. Price, 70 cts.

Water-Sup. Pap. 1330-B. Water requirements of the carbon-black industry. H. L. CONKLIN. Pp. 73–101; figs. 6; tbls. 5. Price, 20 cts.

Water-Sup. Pap. 1356. Geology and ground-water resources of the Henderson area, Kentucky. E. J. HARVEY. Pp. 227; pls. 13; figs. 16; tbls. 13.

Bur. Mines Inf. Circ. 7750. Water Flooding of oil sands in Butler and Greenwood Counties, Kansas. J. P. POWELL. Pp. 42; figs. 18. *Projects in operation 6 to 12 years have recovered 6.6 million bbls of additional oil from the injection of 84.7 million bbls water.*

American Geophysical Union—Washington, D. C., 1955.

Joint Hydrology-Sedimentation Bull. 7. Annotated Bibliography on Hydrology 1951–54 & Sedimentation 1950–54 (United States and Canada). Pp. 207. Price, $1.25.

National Research Council—Washington, D. C., 1956.

The Biological Effects of Atomic Radiation. A Report to the Public. Pp. 40.
The Biological Effects of Atomic Radiation. Summary Reports. Pp. 108.

SCIENTIFIC NOTES AND NEWS

C. S. PICHAMUTHU, former director of geology of Mysore, and Professor of Geology in the University of Mysore at Bangalore, India, has accepted a position to organize and be head of a department of geology at the University of Malaya, Singapore.

The United States Atomic Energy Commission desires graduate geologists with a minimum of three years experience for economic geologic studies in the Colorado Plateau region and for editing of technical manuscripts. Annual salary range $6,390 to $8,990 dependent upon qualifications and experience. Submit Standard Government Application Form 57 or resume of education, experience and personnel history to Personnel Officer, U. S. Atomic Energy Commission, Grand Junction Operations Office, Grand Junction, Colorado.

O. A. GLAESER was recently named to membership on the Board of Governors, Salt Lake City Chamber of Commerce.

O. H. ROSTAD who was formerly with U. S. Smelting, Refining & Mining Co., Salt Lake City has become geologist for The American Metal Co. Ltd., Denver.

P. M. KAVANAGH, formerly with Cyprus Mines Corp., Skouriotissa, Cyprus, has now become chief geologist with Asbestos Corp. Ltd., Thetford Mines, Quebec.

C. E. MICHENER, chief exploration geologist, International Nickel Co. of Canada Ltd., Copper Cliff, Ontario, is now vice president of Canadian Nickel Co., Toronto.

FRANK EBBUTT has recently been appointed chief geologist of the Howe Sound Co. in Toronto. Prior to accepting this position he was in charge of exploration for eastern Canada.

H. C. BROOKS has been named geologist at the Baker field office of the State of Oregon Department of Geology and Mineral Industries.

J. R. VAN PELT will succeed Dr. Grover C. Dillman as president of Michigan College of Mining and Technology.

J. A. PEEPLES, president of the Anglo-Lautaro Nitrate Corp. has joined the firm of Guggenheim Brothers as a partner. He has been associated with the Guggenheim mining interests in Chile since 1927.

J. D. MORGAN, JR., formerly a mineral expert with the Office of Defense Mobilization, has opened a consulting practice in Washington, D. C.

A. E. WALKER, chief geologist for the M. A. Hanna Co. on the Menominee Range, has left for Sao Paulo, Brazil, where he will spend several months in geological work for the company.

F. T. JENSON, Snyder Mining Co. geologist, is at Butternut, Wisconsin, to make a geophysical survey of 2,280 acres of low grade iron ore lands recently optioned by the company.

Large finds of zinc and copper deposits have reportedly been found near the small village of Vazante in the north-western part of the State of Minas Gerias, Brazil, by geologists of the Geological Survey who are working in co-operation with the National Department of Mineral Production of Brazil, under the auspices of the International Co-operation Administration.

The United States Civil Service Commission has announced an examination for geophysicist (Exploration) for filling positions in the Geological Survey, Department of the Interior, and various other agencies in Washington, D. C., and throughout the United States. Some positions may be filled in United States territories and possessions, and in foreign countries. The entrance salaries range from $3,670 to $11,610 a year. Appropriate education and experience are required. For positions paying $3,670 and $4,525, education alone may be qualifying. No written test is required. Information and application forms may be obtained at U. S. post offices, or from the U. S. Civil Service Commission, Washington 25, D. C. Applications will be accepted by the Board of U. S. Civil Service Examiners, Geological Survey, Department of the Interior, Washington 25, D. C., until further notice.

H. C. BROOKS has been added to the staff of the State of Oregon department of geology and mineral industries.

W. R. LANDWEHR, chief geologist of the western mining department for American Smelting & Refining Company, Salt Lake City, received the honorary professional degree of geological engineer from the Montana School of Mines at the 56th annual commencement exercises in Butte, Montana.

O. H. ODMAN, professor in mineralogy and geology at the Royal Institute of Technology in Stockholm, Sweden, starts working this fall with the iron ore research and projecting department of the Grangesberg Mining Company.

K. RANKAMA has been appointed president of the third Winter Conference of Northern geologists planned for 1958 in Helsinki, Finland. Official mailing address for the conference is Fil dr. J. Donner, Yliopiston Geologinen Laitos, Snellmannink. 5, Helsinki, Finland.

B. D. MELLOR is senior geologist for Territory Enterprises Ltd., Rum Jungle, Australia. R. B. LESLIE has been appointed chief geologist in place of W. N. THOMAS who has accepted a newly created position as senior resident geologist at Consolidated Zinc Pty. Ltd. in the Northern Territory.

J. A. FINCH, formerly assistant production superintendent for the Australian Aluminum Production Commission at Bell Bay, Tasmania, is now production superintendent for the Commission.

T. WAKABAYASHI, mining engineer, is now associated with the milling department of Mitsubishi Metal Mining Company, Ltd., Tokyo, Japan.

E. C. SPALDING, mining geologist for Cia. Minera Nacional, S. A., has been transferred from the Plomosas Unit at Chihuahua, Mexico, to the Taxco Unit at Guerrero, Mexico.

C. K. LEITH died sitting peacefully in his chair at his home in Madison, Wisconsin, on September 13.

N. L. BOWEN died at his home in Washington, D. C., in mid-September.

J. D. FORRESTER, dean of the University of Idaho College of Mines at Moscow, and director of the Idaho Bureau of Mines and Geology, has resigned to accept similar posts at the University of Arizona.

D. L. EVERHART, previously acting chief of the Denver exploration branch, AEC, now is geological advisor to the division of raw materials with headquarters in Denver. He reports directly to R. D. NININGER, assistant director for exploration.

R. A. MACKAY has completed a professional visit to Jordan and Persia, and has left the Middle East for Australia, after attending the International Geological Congress in Mexico.

G. A. SCHNELLMANN has completed a professional visit to Portugal and has left London for Chile.

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The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1957–58, with a stipend of $1,600.00. Applications and accompanying testimonials should be submitted not later than February 15, 1957.

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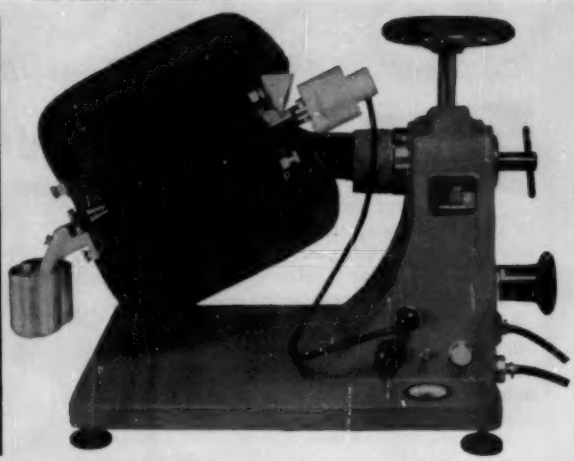

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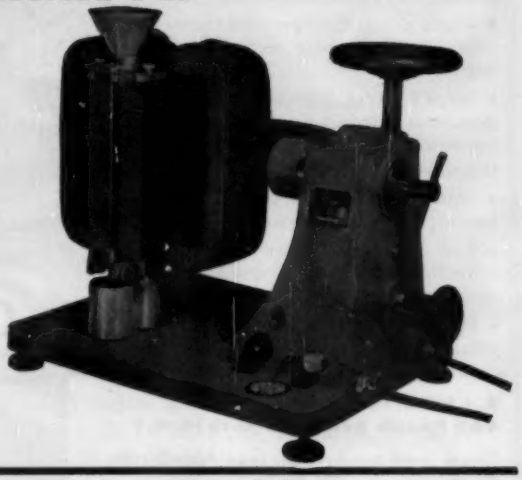

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